Unfolding Perceptual Continua

Edited by
Liliana Albertazzi

Advances in Consciousness Research

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Unfolding Perceptual Continua

Advances in Consciousness Research

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Volume 41

Unfolding Perceptual Continua
Edited by Liliana Albertazzi

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Thomas J. Bata Library
TRENT UNIVERSITY
PETERBOROUGH, ONTARIO

John Benjamins Publishing Company
Amsterdam / Philadelphia

B828.45 . U54 2002

∞™ The paper used in this publication meets the minimum requirements of American National Standard for Information Sciences – Permanence of Paper for Printed Library Materials, ANSI Z39.48-1984.

Library of Congress Cataloging-in-Publication Data

Unfolding Perceptual Continua / edited by Liliana Albertazzi.
p. cm. (Advances in Consciousness Research, ISSN 1381–589X ; v. 41)
Includes bibliographical references and indexes.
1. Perception (Philosophy) 2. Continuity. I. Albertazzi, Liliana. II. Series.

B828.45.US4 2002
153.7'3-dc21 2002018485
ISBN 90 272 5165 7 (Eur.) / 1 58811 241 1 (US) (Hb; alk. paper)
ISBN 90 272 5161 4 (Eur.) / 1 58811 193 8 (US) (Pb; alk. paper)

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John Benjamins Publishing Co. · P.O. Box 36224 · 1020 ME Amsterdam · The Netherlands
John Benjamins North America · P.O. Box 27519 · Philadelphia PA 19118-0519 · USA

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Continua

Introduction

Liliana Albertazzi

Movement is one, but it has different acceptations: what we call the 'one' in many guises. (Aristotle, *Physics*)

Der Ort ist das Bild des Seyen [...] Es folgt hier die metaphysische Grundlage der Geometrie und Arithmetik, aber in höchster kürze. Es is nicht zu vergessen, das man erwarten müsse, ob, in wie fern, der intellegible Raum (Raum welchen die Metaphysik für die Lagenveränderungen intellegibler Wesen construirt) die nämliche Eigenheiten entwicklen werde, welche die Geometer ihrem Raum, den sie der Sinnenwelt entlehnen, zugeschrieben haben. (J.F. Herbart, *Metaphysik*)

Le continu physique est pour ainsi dire une nébuleuse non résolue, les instruments le plus perfectionnés ne pourraient parvenir à la résoundre [...]. (H. Poincaré, *La valeur de la science*)

1. What continua?

One of the areas of greatest interest to researchers in cognitive science, both natural and artificial, is the theory of space-time continua and the tools with which to model them. The approach to these matters has long been one of quantitative analysis which has endeavoured to model the events of the physical world.

In the last decades, investigations into naïve physics (Hayes 1985a, 1985b; Hobbs and Moore, 1985; Allen and Hayes, 1985; Ford and Hayes, 1991), into phenophysics (Petitot, 1994; Wildgen, 1994), into the dynamics of space-time continua (Leyton, 1992; Port and van Gelder, 1995), in the dynamicity of representation (Bickhard, 1980; Drescher, 1986), and in cognitive semantics as well (Talmy, 2000; Lakoff, 1987; Langacker, 1991, and this volume), have highlighted a new approach engendered by a number of specific problems encountered by researchers in artificial intelligence as well (McCarthy and Hayes, 1969).

These problems, some of which also closely concern the development of robotics (Maes, 1990, 1993; Malcolm and Smithers, 1990; Brooks, 1991; Meystel, 1991; Meystel and Albus, 2000), have arisen in relation to concrete situations. For example, how can we recognise the perceptive form, in its dynamic elaboration from the lower to the higher processes, and in the different perceptual fields (Albertazzi, 1998a; Koenderink and Kappers, this volume; Klatkzy and Lederman, this volume)? How can we specify it in its static, moving, solid or fluid appearance, or in its numerous variants of masking, transparency, grouping and amodality, which necessarily involve cognitive integrations? In vision, in fact, even a simple square does not display the 'objective' features of the Euclidean figure, but instead appears somewhat 'sloppy' (Perkins and Cooper, 1980), and similar phenomena are typical not only of visual perception, but also of tactile perception, for example in the perception of parallelism (Koenderink and Kappers, this volume). What is the relationship among perspectives, points of view and unity of consciousness? Every perception of the phenomenal world, in fact, comprises dynamically overlapping, but not coincident, reference systems at different levels of salience (Koenderink, this volume). From this point of view, how can we construct, formally, a *theory of the observer* in the various fields of visual, tactile, auditory, etc., perception, taking also into account of the fact that the choice of particular assumptions, or biases, underlying a model, bears important consequences also in the interpretation of the phenomena (see, for example, the rigidity principle in Ullman, 1979, 1984)?

What is the relationship between the explicit knowledge and implicit knowledge embedded within each other at the level of perception, and how can this relationship be represented? The representationalist approach, in fact, despite its widespread use in artificial intelligence research (Fodor, 1975, 1983), is structurally unable to account for the phenomena of apperception, modalisation, construction and the emergence of new representations unforeseen when the system was programmed.

How can we devise a model of the process itself of concept formation, a model which comprises not only the deductive processes of inference but also productive and abductive ones (Wertheimer, 1938; Peirce, 1903/1998)? How can we account for the difference between the associative process and the functional process in the formation of complexes? Or for the way in which uniform groupings of objects formed according to the standard geometric shapes (squares, circles, triangles, etc.) are dynamically reorganised in perception (and in mental cognition as well) into other groupings based on qualities distinctive of the whole, like colours or textures? And, what is the role of primary,

secondary, and tertiary qualities in the various perceptive fields (Klatzky and Lederman, this volume)?

The complex structure of the perceptive field, in particular, raise innumerable modelling problems concerning its organisation into functional parts of hierarchical wholes, the role of salient features, the relationship among the direction, distance and position of the eye with respect to the visual object and the intensity of light, and so on, all of which are aspects that make the *description of images* extremely difficult. Some of the problems to be addressed, for example, are how to break images down *naturally* while taking account of the 'ontological' differences among the parts of which they are composed, or the importance of the surroundings when identifying patches (small patches, in fact, appear very differently according to their ground: Koenderink and van Doorn, 1979b) or the role played by some important parts of the image like relief or chiaroscuro (Palmer, 1999, Ch. 6).

Again, how can we formalise the visual or auditory perception of art works, given the dynamic relationship among structure, form and content in music, architecture, painting, sculpture, bearing in mind that the perception of art is not reducible to the mathematical modelling of sensible material? Or, how can we model the actions of daily experience, which always comprise a field salience and empathic traits, and which cannot be predicted on the basis of physical laws?

How can we represent the multi-signifying expressions of natural language which, besides logical-syntactic, inductive and deductive inferences, makes ample use of elliptic, metaphorical, analogical and emotive devices which do not follow a mere computational logic (Lakoff and Johnson, 1999; Albertazzi, 2000a)?

And in this regard can one distinguish a continuity among the world of experience, action, conceptualisation and linguistic expression in which the transposition of invariant structures among different fields can be discerned (Wilcox, this volume)?

Research into these matters, despite their thematic diversity, increasingly reveals shared features, most notably:

1. Adoption of a *dynamic* and *qualitative* paradigm instead of a merely static one. In fact, even the classification of objects under observation change, accordingly to the description adopted.
2. An endeavour to configure an Aristotelian rather than Cartesian theory of knowledge which reflects the structures of the *perceptive world* and not merely abstract 'mental states' (Allen and Hayes, 1985; Ladkin, 1987).

3. A search for a *direct* and *concrete* theory of intentional reference, but which is compatible with the assumption of inner representation of knowledge (Smith, 1996).
4. Consideration of the *qualitative modes of change* and *unfolding* of the states of the perceptual system(s) (Port and van Gelder, 1995).

The problem at the moment, it seems, is the nature itself of presentation, for it apparently possesses a *granularity* and a *multi-level inner stratification* (Shanon, 1993; Albertazzi, 2001b. See also Klatzky and Lederman, this volume) which requires some sort of *convergence* between a *realist grounding of reference* (Gibson, 1979) and a *constructivist dynamics of the mind* (Penrose and Penrose, 1958; Penrose, 1968; von Glaserfeld, 1978, 1984; Ullman, 1980. On the Gibsonian approach see Lappin and van de Grind, this volume). In other words, the nature of representation requires a *new psycho-physics* which takes account of both the processes involved in the formation of the *environment*, operations and manipulations included, and the *correlated processes of its inner presentation* (a similar approach in Shepard, 1975; Shepard and Chipman, 1970; Shepard, 1984. See also Koenderink, this volume; Lappin and van de Grind, this volume).

Moreover, given that the objects of the perceptual world are not Euclidean, one understands why revision is currently under way of the nature of space-time continua and of their base primitives. The abstract primitive geometrical concepts of 'point,' 'line,' 'surface,' or categories of formal logic like 'individual,' 'set,' or relations like 'before/after,' are not capable of depicting the contours, overlapping or masking of perceptive objects, or their movement, distance, velocity, position or displacement in perceptual space and perceptual time. Even less do they seem able to represent the dynamic complexity of the higher mental processes, except at the computational and inferential level.

In actual perception, for example, even the mathematical notion of 'density at a point' is troublesome, because factually we have to analyse the spatial distribution of the qualities of the perceptual field *at many inner scales* and *simultaneously*. Simultaneously, in fact, we pick up information at different levels of resolution (Koenderink, 1991).

Although recent attempts to analyse continua of space, time and movement (Allen and Ferguson, 1994; Galton, 1995, 1997), have emphasised the need for a *qualitative* description of phenomena, they use formalisms which once again demonstrate the difficulty of modelling simple facts frequently manifest in perceptive fields.

In general, the problems involved in the modelling of phenomena concern three possible types of deficiency:

1. Deficiencies *de facto*, i.e., the use of erroneous tools for the phenomena to be analysed.
2. The *actual* inadequacy of the tools used, which implies that simplification of the phenomena themselves is necessary.
3. Deficiencies *de iure*, which concern the nature itself of the phenomena under observation, and which exclude, in principle, a specific type of modelling.

Effectively, in its diverse ambits of analyses, cognitive science must understand, explain and model very different phenomena, for example:

1. The gradual vanishing of a light, the rise or fall of warmth, or even the gradual dwindling of an odour in a room (phenomena which are not strictly of open/closed, on/off, before/after type), or the apparent forward-backward-downward movement of a body, the transformation of the shape of the clouds by the wind, of a piece of clay by manipulation, or the emergence of new 'objects' in vision, through blurring.
2. The cognitive stratification distinctive of 'amodal' objects of perception like optical-geometric illusions, stereokinetic movements and perceptive causality (phenomena at odds with the spatial concept of mathematical 'extension' because structurally they require a subjective completion) (Gregory, 1998; Albertazzi, this volume; Koenderink, this volume).
3. The qualitative change that takes place in psychic and perceptive states (prior to the distinct perception of the 'simultaneity' and 'succession' of the parts) and the complexity of their order in the actual duration, which 'contemporaneously' displays features of simultaneity and succession (Benussi, 1913; Libet et al., 1979, 1982; Albertazzi, this volume; Koenderink, this volume).

In other words, most of the formal methods used to date seem at least partly deficient in modelling the *perception of form*. Such perception comprises, for example, *displacement of parts* of the perceptive content or reorganisation of physical sequences on the basis of *qualitative saliences*, or *amodal perceptions* as exemplified by Kanizsa's triangle, which are not entirely and immediately classifiable as 'mental' and/or inferential since they show a character of 'encountered presence' (Benussi 1923–1925; Metzger 1941; Kanizsa, 1991; Albertazzi, 2001b).

Most of all, since in perception we have forms at different levels of unfolding and at different levels of resolution, we must also deal with parts and wholes at different level of granularity. For example, we must deal with several boundaries and sub-boundaries, each other dynamically interwoven (Koenderink and van Doorn, 1986: 395; Burigana 1996).

These considerations suggest that we must re-think the nature of the primitives of a *common-sense qualitative Aristotelian physics*, while delineating a *descriptive* theory which lays the basis for analysis of those primitives. In doing so, we may also discover that we possess neither a psycho-physics suitable for description of numerous phenomena of form (from the figure/ground configuration to phenomena of intermodal perception) nor a logic or mathematics totally adequate for their representation (Koenderink, this volume). What currently and generally happens in the formal analysis of perception, in fact, is that logico-formal deductive, inferential presuppositions are chosen which do not always fit the complex nature of perception (see, as an example, Bennett et al., 1989: Introduction).

On the basis of these considerations, the book analyses perception in the various sensory fields as providing prime access to the problems of consciousness, starting from the observation that the structure of actual perception is such that *the perceiver is directly part of the event presented* and thus constitutes a *direct source of information*. From this point of view, the object of neurophysiological research (brain scanning) and the object of psycho-physics (the psyche or, in modern terms, the mind) do not coincide. This distinction is one of this book's non-reductionist and ecological presuppositions *vis-à-vis* perception. Consequently, the construction of an ecology-based psycho-physics entails a theory of *direct reference* which depends at least partly on the state of the observer, and a theory of perceptive space-time which is intrinsically subjective (Koenderkink, 1999; Lockwood, 1989; Albertazzi, this volume).

The book deals in particular with the nature of the cognitive processes involved in perception. To do so it adopts the particular point of view of the *phenomenal continuum*. The problem of the continuum, in fact, besides having strong evolutionist value for the survival of animal species, poses a series of intriguing puzzles for the theory of representation. For example, what do the leap of a frog, the gesture of a ballet dancer and the continuity of a melody have in common? What are the invariants that lead from perception of the movement to the representational discontinuity of the images? What is the relation between the representation of the continuum and the semantic and psychic content of the acts represented? Or what is it that connects together a sequence of external figures closely structured into internal modules as im-

ages of a narrative, like the figures carved on Trajan's column (see Pierantoni, this volume)?

2. The neo-Aristotelian legacy

One of the characteristics of a neo-Aristotelian physics is that it displays features which are more *intuitively geometric* than algebraic or analytical – of a geometry that we may call *empirical* and *intrinsically subjective* because it is based on the *cognition of forms* (Albertazzi, 1998b).

This is not a new intuition. Traces of it are to be found in the medievals, but it was mainly at the end of the nineteenth century and the beginning of the twentieth that the problem returned, in new guise, in the debate on the foundations of geometry and in attempts to arithmetise the continuum. Less well known is the fact that, during the same period, the problem of the continuum aroused the interest not only of mathematicians but also of psychologists and philosophers.

The concept of multiplicity or the concept of dimensionality in its various versions were part of a scientific milieu that combined geometry, the physics of nature, experimental psychology, and metaphysics, and whose protagonists were physicists (W. Weber, Fechner, Helmholtz), philosophers (Lotze, Mill, Ueberweg, Brentano, Husserl, Erdmann), mathematicians (Cantor, Riemann, Pasch) and psychologists (Wundt, Stallo). Most of those scientists, indeed, shared a multidisciplinary competence in various ambits of research.

At the beginning of the twentieth century, the continuum was addressed, for example by Cantor on the basis of his set theory, as a particular type of infinity, and something which could be *constructed* starting from *elements* (Albertazzi, 1989). In the same period theorems were found (for example by Peano) which undermined the *prima facie* natural idea of dimension; theorems which showed that the cardinality of the points of the three-dimensional space of a two-dimensional surface and of a one-dimensional line is the same (theorems obtained paying the cost of destroying the connections of proximity among points).

However, at the end of the last century, like today, the true problem in dealing with continua consists, firstly, in the fact that the 'continuum' to which authors refer is *not* always the same; or better, that these Authors refer to different 'aspects' of the (same, however stratified) psycho-physical continuum (on the multifarious facets of the concept of continuum see Pierantoni, this volume). The fundamental fact to be noted is that what we can define the 'physical' and

the 'perceptual' aspects of the continuum are distinguishable *only conceptually*: factually, we refer to one and the same continuum, whose 'objects' can be seen, heard, smelled, touched, etc., but also rotated, manipulated, fixed in one or two more points (for example a disc), so to limit their liberty of movement in space. An important issue, therefore, is the distinction between the *aspects* that *directly pertain to the object* – like the so called by Hering 'inherent' colours (the 'jellow' colour, for example, of the lemon), or the orientation that makes the difference between a square and a diamond – and those that *depend on modes of our apprehension* of it, like distance, position, direction as in the visual field, happens, for example.

To grasp the complexity of the situation one need only consider the following question: are the spatio-temporal relations of objects – for example, the temporal relations of 'before' and 'after' – absolute or relative relations? That is to say, does the fact that they depend on a specific observer mean that we can only speak of them in terms of their *subjective individuation*? Moreover, how should one distinguish the *phenomenological* point of view of spatio-temporal relations – for example, the fact that I am directly aware of two distinct instants of time – from the *conceptual* point of view of the same relations (a problem that was widely analysed in the early 1900s. See for example Robb, 1921)?

Those questions show as the problem of the *ontological reality* of the continuum is closely connected not only with (1) the so called '*physical reality*' but also with the (2) *mathematical form of description* applied to the contents of perception and/or of thought and (3) with the '*phenomenal givenness*' of the continuum in the various perceptive fields that regulate the perception of forms and movement (Klatzky and Lederman, this volume; Kennedy, this volume; Vicario, this volume; Kappers and Koenderink, this volume). The true problem concerns the isomorphism and the comparability of the three aspects.

Another specific question concerns the interplay and intrinsic connection between the physical and perceptive aspects of the continuum: are they effectively distinguishable (and not solely at the level of epistemological abstraction), or are they different faces of the same *psycho-physical* series of events?

A further issue is the problem of *measurement* that, as both stable and less stable proprieties of objects are concerned, at the end of the nineteenth century was of crucial importance in both mathematics and psychology, and consequently had a crucial bearing on the debate on continuum. For example, the scientific debate of the time evidenced the importance of questions like the following: when we say that two bodies are of 'equal length,' what do we mean? What do we mean with terms like 'rigid,' usually adopted when referring to a unit of measure (a meter, a rod, etc.)? In what sense do those terms refer to the

characteristics of existent bodies (whose measure is always undetermined till a certain extent) which can be stretched, curved, distorted, etc.? How do these terms refer to objects like waves or flames or to materials like clouds and wisps of smoke (for a modern approach see Shepard and Cooper, 1982)?

In the last of these cases, in fact, we have to deal with objects which simultaneously show both changing and permanent components. Moreover, the matter is even more complex at the perceptive level than at the physical level of the world of nature: for cognition of every type of perceptive object through oculomotor and kinaesthetic movement results from an intrinsically *dynamic* construction of the processes internal to imagery (Husserl, 1983, 1988/1997; Albertazzi, this volume).

From the foundational point of view, an issue central to the debate on the continuum since from the outset, although it was one certainly not addressed with any great lucidity, was the problem of *psychophysics* (Fechner, 1860).

While some scholars inquired into the relationships between *external* physical phenomena and *sensory* perceptions – comprising all the complexity of sensations – and how to express these relationships, there were others who asked, in a different disciplinary area, how to achieve the transition *from an empirical geometry of intuitive space* and its intrinsic relations *to the idealisation* of the latter in Euclidean form, and thereafter their elaboration in Helmholtzian, Riemannian, Cantorian, or other terms.

The problem of reconstructing these intricate relationships is complicated by the fact that after Hilbert, and above all in Tarski, lost was the more properly *cognitive* ('psychologistic' in nineteenth century terms) aspect tied to the question of foundations. Yet a Herbartian tradition (for instance with regard to the difference between sensible and intelligible space) still thrived, especially in Riemann (Herbart, 1824/1825, 1893; Riemann, 1892, 1923) – as evidenced by the criticisms brought by Lotze, Brentano, Husserl, as well as others, against Riemann's conception of variety, even though they themselves had been influenced by it (Husserl, 1891, 1983; Becker, 1923).

These criticisms centred on three assumptions in particular:

1. The *ontological* commitment of the same *cognitive processes* that lead to elaboration of the concept of continuum (with a special reference to Herbart, 1824/1825, 1893).
2. The relationship between the *space* and the *time* of the *perceptive qualities* and the *structure* of the *mathematical operations* which formalize it.
3. The transformation of the primitives of an *empirical* geometry into elements of an *algebraic* geometry: for example, the translation of the concept

of 'thick points' or 'part of space' into the spaceless mathematical concept of 'point' (analogously, from the point of view of temporal continua, 'thick points' are extended, or non-punctiform, 'moments-now'. See below).

In particular, an *empirical theory of continua* as a *descriptive theory of the phenomena of perception* (also based on psychological experimentation in the laboratories) as been developed by authors belonging broadly to the tradition of descriptive psychology that sprang from Franz Brentano's theory of intentional reference (Brentano, 1874/1973). Surprisingly, the theories of these authors display close similarities with aspects of contemporary research, and for this reason are of great interest.

Moreover, the simple fact that researchers working in the field of artificial intelligence make occasionally reference to these theories (Dreyfus, 1984; Smith, 1996) is good reason for clarifying their arguments, given that they are not widely current, and often misunderstood.

3. Continuum and intentional reference

Descriptive psychology has a twofold character, *theoretical* and *empirical* (even *experimental* in its developments). From a theoretical point of view it is a variety of neo-Aristotelian metaphysics developed on a scientific basis (mainly psychology, but also mathematics) and using a scientific method. From an empirical and experimental point of view it has given rise to the two branches of Gestalt psychology (those of Graz and Berlin), although its indirect influence has been much greater: in fact, authors like Stern, Rubin, Brunswik, Bühler, Selz, Michotte, Fraisse, Thinès, Gibson, Kanizsa, etc., belong to this tradition, although not all of them can strictly speaking be called Gestaltists (Albertazzi, 2001a).

At the origin of these theories is the doctrine of *intentional reference* today often over-simplistically identified with a *semantic theory of intentionality* whose representative scholars, especially within the analytic tradition, are generally considered to be Searle, Dreyfus, Dennett and Davidson (Davidson, 1980; Dreyfus, 1984; Dennett, 1987, 1991; Searle, 1992). However, these contemporary theories of intentionality – some of which have played a significant role in the revival of phenomenology in artificial intelligence research (Winograd, 1972; Dreyfus and Haugeland, 1978) – have almost nothing to do with the original conceptions of descriptive psychology. This claim will become clear in the discussion that follows.

It would be beyond the scope of this Introduction to describe Brentano's metaphysics, which we may call a sophisticated *theory of proprioception* (Brentano, 1933/1981) developed in opposition to a nineteenth century 'chemistry of the soul.' The latter, in point of fact, has a close bearing on the contemporary 'representational theory of the mind' (Fodor, 1975). Here I shall briefly review its main tenets, which relate closely to elaboration of a theory of perceptual continua (Brentano, 1928/1981; Albertazzi, 1998b).

Very crudely put, according to Brentano, an *act of intentional reference* is directed at an object of a certain type, given in *actual presence*, (primarily) in perception (touching, hearing, seeing, etc.) and in mental representation (imagining, desiring, remembering, etc.). Again very crudely put, there are *acts* of 'seeing' something, 'hearing' something, 'touching' something else, while the *objects* 'seen,' 'heard,' 'touched,' 'smelt' (a colour, a sound, a touch, an olfactory perception, etc.) triggered by the external world, are '*internal objects*' to the acts (Brentano, 1874/1973).

On this view, *representation is wholly internal*, although it is based on *acts* of *perception* of the environment. The acts of intentional presentation (or psychic phenomena, *Vorstellungen*) therefore indicate that 'something (*etwas*) manifests itself psychologically' to consciousness and has an *ontological* ground – like the elements that underpin particular sensible states. In many respects, this position, which rests on J. Müller's theory of specific energies, is close to the contemporary stance taken up by scientists like Shepard and Gibson (Shepard, 1975, 1984; Gibson, 1979) although it does not wholly coincide with it. The difference resides in the fact that, although intentional reference is *direct*, it *intrinsically involves* the subjective structures of presentation. These theories, in fact, entertain an idea of *geometric imagination* which springs from Herbart's concept of *serial forms* (*Reihenformen*) as an integral part of the theory of continua (Herbart, 1824/1825).

For Brentano, intentional presentations are concrete *spatio-temporal events* of psychic energy or activity. They act as 'pointers' towards an *inner* object of some kind, and primarily towards phenomenal objects like the *patches* of colour, sounds, odours and tactile perceptions given in an actual present (from an experimental point of view see Klatzky and Lederman, this volume; Vicario, this volume). The ground of these phenomena is proximal space – that is, the visual, auditory, tactile, graspable phenomenal space of our everyday experience. We characterise the phenomenal space through our sight (shape, size, position, movement), touch and kinaesthesia (shape, size, distance), hearing (direction of sounds) and olfaction (direction of odours). From the phenomenological point of view of actual perception, we immediately perceive not yet 'ob-

jects,' but 'moments' 'aspects' or 'strings of events' (a similar point of view in Buddhist logic: see Stcherbatsky, 1962:65).

As said, underpinning this inner psychophysics is J. Müller's theory of specific energies, according to which it is not external *stimuli* that are perceived but the *contents* of the nerve fibres, these being *signs* of transcendent objects. The next step, which we owe to Brentano, is to consider the content of the fibres *modified* in the structure of intentional reference as an *attribute of the subject* (Ingarden, 1969). Consequently, Brentano's metaphysics is erected on a *qualitative continuum* in which time and movement, time and form are *covariant* (Albertazzi, 1999a). The main criticism brought by Brentano against the mathematical theories of continua of his time, and in general, was that they drastically reduced the 'extendedness' of perceptive phenomena to 'quantitative metric extension' and sought to construct geometry from algebra (Brentano, 1976/1988, Albertazzi, 1999b, Ch. 2, and this volume. On the problem see Pierantoni, this volume).

Brentano's theory thus highlights some crucial nodes of the question of the continuum, among which the nature of perceptive space-time (Lappin and van de Grind, this volume), the problem of the 'inner' aspect of psychophysics (the *inner* character of *presentation* of the outside world: see Kennedy, this volume; Koenderink and Kappers, this volume), the problem of measuring perceptive phenomena (what do we measure, the *act*, the *object* or the *content*?), and the problem of how to model phenomena correctly.

One aspect to bear in mind, therefore, is that an empirical theory of continua is *prima facie* a *descriptive theory of phenomenal continua as they appear in the various perceptive fields*. In principle, it lies at the basis, but it is not identical with, the continua of abstract mathematical theory. A mathematical theory of continua, in fact, makes use of a preliminary *series of operations* of abstraction and idealisation through symbols which do not pertain as such to a foundational analysis of the primitives of perception.

Obviously, treatment of perceptive continua covers geometric and mathematical concepts understood in a general empirical sense, like the concepts of 'spatial perceptive extendedness' or of 'boundary' (see below, and Albertazzi, this volume). Then, the fact that from a perceptive point of view fields are *qualitative* in character, and that their analysis tends largely towards *morphological* description, in principle does not rule out the possibility of a quantification of phenomena in the various perceptive fields, as demonstrated by further experimental developments of the theory.

Finally, the treatment of perceptive continua also deals with certain features of the *physical* continuum, which support them but are *distal stimuli*, in

that they never come directly into contact with the psychic world, but only do so indirectly *via the modes* of the intentional presentation (and of neurophysiological activity, obviously, which however is not our concern here). (On this aspect in tactile perception see Kennedy, this volume).

A crucial aspect of a Brentanian conception of continua concerns the identity, the pre-existence and the wholeness of the 'objects' of the actually perceived world, which in their multiform appearances always exhibit at least two types of stability: a *spatial* extendedness, i.e., the space of figures from 'point' to 'point,' from 'line' to 'line,' and so on; and a *qualitative* extendedness, for example, the 'space' of colours, the 'space' of sound, and the like.

However, the 'points,' 'lines' and 'surfaces' of the perceptive world are *not* immediately points, lines and surfaces in the Euclidean or mathematical sense. They still possess thickness, irregularity, colour, texture, and so on, and their perceptive space displays forms of stretching, cutting, distortion, ambiguity, overlapping, etc., which are *closely interwoven with objects* themselves (see Albertazzi, in this volume). In fact, also the stimuli that excite the retina arouse the presentation of an extended surface which, however small it may be, is *not* punctiform.

In perceptive space, moreover, we deal with *functional wholes* which are not the result of the mere coupling of independent spatial-temporal structures of *combinatory* type, on the one hand, and *atomic* objects of some type on the other.

Perceptive objects, in fact, display a substantial *interdependence* between the *time and space* of their *occurrence* and *typicality*. This has been shown by analyses of such phenomena as the perception of causality (Michotte, 1957, 1963), the tunnel effect (Burke, 1952), the tau and kappa effects (Benussi, 1907a, 1907b; Abe, 1936, 1937), where perceptive space-time and the specific nature of the phenomenon are inextricably bound up with each other (Albertazzi, this volume). The *location* of an object in the visual field depends on numerous, *functional interdependent factors*, ranging from specificity of colour and quality to degree of brightness, and it is the result of a complex mental process of *direction by the perceiver towards the actual configuration of the field* or *a part* of it (on the vantage point in vision see Kennedy, this volume).

The only way to understand what truly constitutes an *act of intentional presentation*, then, is, *prima facie*, to have in one's hand a *map of the morphogenesis of the perceptive structures and of their objects*. This approach is essentially dynamic, in the sense that the morphogenesis of the perceptual forms is an integral part of the shape description (Albertazzi, 1998b), which also means that we need a new theory for their *measurement* (Koenderink and van Doorn, 1986).

The idea of producing this book was substantially prompted by these latter considerations, and the various contributions in it highlight the complexity of the intentional reference in the various perceptual fields.

4. The moment-now

At the end of the century, analysis of the intrinsic complexity of the continuum pointed up one of the theory's crucial aspects: the relationship between 'instants' of time and 'points' of space (and/or of place). The problem, which was addressed in paradigmatic fashion by physics and geometry, was of central importance as regards, for example, the question of the temporal simultaneity of events in the theory of relativity. But more in general it raised the issue of the cognitive individuation of the space-temporality of events. With regard to movement, in fact, the question was framed as follows: whence derives our awareness of the distinction between two or more instants of time as one *preceding* the other? Put in these terms, the question gave rise to new concepts of order (for instance those of conical order, Robb, 1921), of instants, points and lines.

Thus, both within specific epistemological theories and more generally in theory of knowledge, it was the *structure* itself *of the representation* that was questioned, and specifically as regards the presentation of two instants and their temporal difference in terms, for example, of 'before' and 'after,' 'simultaneity' and 'succession.'

These aspects were explored not only in physics but also in experimental psychology (Wundt, 1896; Meumann, 1883/1884; Benussi, 1913; Bonaventura, 1961) and in ontology (Meinong, 1899, 1904. On this see Albertazzi, 1996a), giving rise to detailed analysis of the temporal microstructure of cognitive processes. The question that these authors sought to answer was whether the act of presentation of two temporal events also implicitly comprised cognition of their relation, or whether such recognition was due to a different act superimposed on the previous one. Amongst other things, this required elaboration of a new theory of the judgement (see the concept of 'potential action' in Koenderink, this volume).

Further experimental analysis of the perception of temporal events at the psychophysical level evidenced the importance of the 'time of presentness' (James, 1890; Stern, 1897; Benussi, 1913) and the occurrence of phenomena of temporal inversion (Benussi, 1907b). This once again raised the problem of the 'arrow of time,' given that extremely brief sequences of temporal intervals

display dislocations in the perception of the order of the stimuli, which at the phenomenal level are shifted 'forwards' and/or 'backwards' (Vicario, 1973, and this volume; Albertazzi, 1996b, 1999b).

One crucial finding of this theoretical and experimental analysis was awareness that the 'instants' of perceptive and mental time in the broad sense are *not punctiform* but endowed with an intrinsic *elasticity* irreducible to mathematical extension.

Taken together, these various insights (though they have necessarily been simplified here) yield an idea of the importance for a theory of perceptive continua of the *moment-now* (the 'here and now' of actual perception).

In fact, before constructing a formal theory of the representation of perception as the manipulation and transformation of its concrete features, a theory of the perceptive continua begins with description of the origin of perception as the coupling of diverse fields or systems given *simultaneously* and with *differing degrees of pregnancy* in actual perception. The moment-now, in fact, comprises the *concrescence* of many actual events to form an actual whole (note that 'concrescence' is both a term in Brentano, 1982, and in Whitehead, 1929. On the levels of presentation of objects in haptic field see Klatzky and Lederman, this volume).

The moment-now is some sort of phenomenal 'point-zero:' however, this point-zero does not lie at one or other extreme of the continuum, but rather at its *centre*, where it faces in two opposite directions and constitutes the continuum's natural *boundary*, that of the *current position of the perceiver*. As Metzger pointed out when discussing one-dimensional continua, the phenomenal 'point-zero' lies between light and dark, between hot and cold, between muscular contraction and stretching, between happy and sad, and so on, and not at the extremity of the two opposites (Metzger, 1941).

If we transfer this situation as regards the individual continua of space, time, sound, and so on, into the complexity of actual perception, we gain understanding of the *role of proprioception* as the *actuality of the multiple and multiform continua* of the various perceptual fields 'held together by the act of intentional presentation in the concrete 'here and now' (also in Brentano, 1976/1988. See Albertazzi, 1998b, and this volume). The likelihood that new representational configurations will emerge at the functional level is so great that it thwarts any attempt to analytically *define the system a priori*.

A different problem, although it relates closely to the one just discussed, is the relationship between the *singularity* of the elements presented 'here and now' of concrete perception and the *representational continuum of consciousness* as a process, that allows the past to be recovered and the future predicted in a

unidirectional temporal order, so that at that stage we can identify a 'before-after' relation. This aspect has led to theorisation of *intentionality* as the *continuity of the sequence of temporal boundaries* (Husserl, 1966; Benussi, 1913. On this see Albertazzi, 1996b, 1999b. On some structural aspects of the question see also Pierantoni, this volume).

The fundamental characteristic of presentation, in fact, is that it is essentially *temporal*. Every simple perception, even of an object apparently at rest, springs from the cognition and assumption of previous different states of the object. These previous states are inferred from the *indices* of directionality (verticality, horizontality, obliqueness, etc.) as well as of position and order in the field (behind, in front, to the left, opposite, etc.) given in the present (Kennedy, this volume; Albertazzi, 2000b). This is a *constant feature* of presentation: the perceptual field comprises numerous direction lines or escape points corresponding to the *locus positions filled by the various types of phenomenal content* (colour, shape, texture, etc.). The visual field as a whole, therefore, takes the form of a *system of positions with a continuous ordering*.

Thus *cognition of a simple shape* requires the mind to *review the entire sequence* of shapes leading up to the current one. The past states of the object represented are *embedded* and *presented* within the present (Albertazzi, 2001b). The important point is that construction of the whole, and the *causal* connection among the different temporal states of the presentation related to the external stimuli, are a *product of internal reference*: what has been recently called the 'asymmetry principle' (Leyton, 1992).

The moment-now, therefore, restores not only the series of states given in the present, but also the memory of previous states – that memory due to the structure of intentional reference which connects the *contents* of the individual states of the objects represented together, giving them an *order* and a *position* within the *presentative continuum*, which then tries to reconstruct them (Husserl, 1966). From this point of view, the simultaneity of events is the simultaneity of those events which occur at the same 'place' of our subjective space of presentation.

A further important point to bear in mind is that, although reconstruction of these processes takes place internally, it *refers directly* to the events of the *external world*, and therefore *simultaneously endeavours to reconstruct the processes* responsible for the formation of the environment (Koenderink, 1984a; Leyton, 1998). From this point of view, a theory of intentional reference is not immediately ecological *à la* Gibson but, as said, requires a sophisticated *psychophysics of the perceptive-presentational and representational continuum* with two facets – one internal the other external – but which is not couched in parallelis-

tic terms (Brentano, 1976/1988; Albertazzi, 2001b; Pierantoni, this volume). A psychophysics of this kind should be able to account for the *functional constraints* operating within the system, or in other words, for the *structure* and *modalities* of direct intentional reference.

A theory of intentional reference, as the various studies in this book will try to show, also requires an *empirical geometry* of space, time and the qualitative forms.

5. Space, points of space, parts of space

Here I shall discuss only some of the concepts furnished by empirical geometry with regard to perceptive continua, mainly on the basis of Ueberweg's argumentations, one main source of Brentano (Ueberweg, 1851; Brentano, 1976/1988). These concepts have given origin to the notions of:

1. *Space* as a *homogeneous continuum of places* which is able to divide itself and to extend itself infinitely from any whatever part that a body may occupy, and in any whatever direction that it may move.
2. *Points* as *indefinitely small spaces* (Ueberweg, 1851; Brentano, 1976/1988; Husserl, 1983).

Detailed examination of the theory in its entirety would be beyond the scope of this Introduction. I should point out, however, that has consisted principally in analysis of the *movement* of the *solid and rigid bodies* which largely constitute the world of our perceptive experience as well, and concerning which we try to state 'rules' from a specific point of view. The point of departure for a kinematic geometry of this kind is therefore closely similar, from a psychophysical point of view, to the 'rigidity assumption' of contemporary research on which the invariants of the ecological theory of perception are based: a point of view, for example, developed by Ullmann, who seeks to reconstruct the variability of the points in the continuum of the two-dimensional images of perceptive forms on the basis of the invariability of the points in the continuum of three-dimensional objects (Ullman, 1979, 1984. See also Musatti 1924, 1937; Gibson, 1950, 1979; Johansson, 1950). According to Ullman, a set of elements which undergoes a two-dimensional transformation, which has only an interpretation as a rigid body moving in space, must be *interpreted* as such a body in motion (Ullman, 1979: 146, but also present in Musatti, 1926. On the experimental developments of these aspects see Lappin and van de Grind, this volume).

Secondly, it is worth noting that this analysis does not start with 'point' as an undefined non-mathematical concept. Instead, it endeavours to give the notion systematic conceptualisation, as it does with straight line, plane, surface and three-dimensional space.

Thirdly, this empirical geometry regards the perceptive objects of our daily experience as dividing between a set of *qualities* (e.g., a certain shape, a certain colour, etc.) and *relationships* of spatial position with respect to other objects (e.g., if the object appears to be lit up, masked, etc.). For example, the perceptive object in the visual field stands out as something *unitary* and *invariant* when it is separated from these positional relationships with other objects in space (Lappin and van de Grind, this volume). We perceive the *shape* of an object relative to (and simultaneously with) its position in space, its direction, distance, velocity, etc. Indeed, these latter *relational qualities* are one condition for the (phenomenal) *identity* itself of objects (Musatti, 1926: vii). Figural and relational qualities, therefore, perform different roles in the overall structuring of the perceptual continuum (Albertazzi, 2001b).

On these premises, the point of departure for an empirical theory of continua is the following: in perceptive experience, the identifying, separating or *fractionalising* of 'space' by the total sensible intuition takes place through the *perception of movements*, or in other words, through the *modification of distance and position*. When we see a moving body, something is altered as it moves and something else remains unaltered in the field. Therefore, movement is primary in an empirical geometry, and the *place* (*Ort*) is what is *altered in movement* (Ueberweg, 1851). This point, indeed, is also at the basis of the figure-ground scheme in Gestalt psychology: in fact, in the perceptive field, what is given as 'figure' normally is 'what is in movement' (Koffka, 1935; see also the case of induced movement in Duncker, 1929. See also Lappin and van de Grind, this volume).

When a body moves, something in the perceptual field is modified by virtue of its movement and something remains the same, so that a division, a *separation*, occurs. A rotation, for example, is the movement of a stable spatial configuration of which one or more elements remain immobile. Moved bodies may occupy another place, passing through successive places as they do so, because the places are homogeneous. The places occupied by a moving body follow each other with indefinitely small differences, so that the alteration of the place of the body in movement also proceeds through infinitely small differences and *appears* to be smooth. If we *unify its various trajectories*, we have a continuous set homogenous in itself: therefore, a magnitude that can be increased or reduced by non discrete differences is called 'smooth.' (Recent

developments of the so called 'visual potential' of the objects described as a graph structure are in Koenderink and van Doorn, 1979a; Koenderink, 1984c. See also Lappin and van de Grind, this volume.)

From these preliminary considerations derives the empirical 'theorem' that there exists a continuum of places homogeneous in itself and able to divide itself and extend itself infinitely from any part whatever that a material body can occupy. This continuum is open in all directions and is called 'space,' as a homogeneous series of positions (*Stellen*) (Ueberweg, 1851).

The fundamental properties of perceptual space are therefore homogeneity, continuity and infiniteness. A finite part of this infinite space is called 'a space' or a geometric body. Consequently, there does not exist, perceptively, a simple non-extended spatial element like the mathematical point, which instead can only be fictionally 'assumed' in the imagination. Empirical and descriptive analysis only recognises 'the indefinitely small space' – that is, the *progression of the division*. A crucial feature of the theory, then, is that a geometrical point is only an idealised location, because perceptual points have an *intrinsic structure*. From a *perceptual point of view*, in fact, a 'point' is *a location with different possible directions*: points may have parts and coincide with parts, exactly as parts may coincide among themselves (see below, and Albertazzi, this volume; Koenderink, this volume).

The *totality of all the 'points'* (infinitely numerous) – a totality which consists in one or more *continuous forms*, which can occupy a *position* in the continuum, and which satisfies a certain condition – is called the continuum's 'geometric locus' (Ueberweg, 1851). The point to bear in mind is that the continuum essentially concerns *Gestalten* which imply *subjective* features and perform the role of 'higher order objects' to express relationship among spatial 'elements' whose treatment would otherwise be cumbersome to treat: the relation might be understood in terms of an analogy, with the role played by the 'square' – in Euclidean geometry – *vis à vis* linear treatments of space.

6. Boundaries

One of the most difficult points to grasp in a theory of Brentanian type is the nature of *spatio-temporal moments-now* (*Jetz*) as boundaries of the continuum. Since these are acts of psychic energy which do not presuppose a conception of enduring substance, how can their continuity be explained? Are there intervals between the various moments-now? In general, do intervals exist?

The concept of boundary plays a key role in a descriptive theory of the perceptive continua. This is not the mathematical concept of *approximation*, but, again, rather a concept specified on the basis of observation of a movement, and it pertains to a deduction of perceptual space from the concept of *sphere*, something similar to Huntington's disc model from the point of view of modalisation (Huntington, 1913. See also Koenderink, 1984a, 1984b). Analysis of this type yields some empirical 'definitions,' for example (Ueberweg, 1851):

1. The *place* (i.e., what is altered in movement) of the movement of a point which is perceived *stably* connected to a fixed point of the spatial continuum is called the 'spherical locus' (*kugelisch*).
2. A fixed point around which another one is perceived stably connected to it moves is called the 'central point' or *centre* of the spherical locus.

Characterisation of the spherical locus is based on the homogeneity of space. Once a body has been fixed in one of its points, it is unable to reach all possible places without restriction, so that the spherical locus separates a finite space (to which the fixed point belongs) from the remaining infinite space. Given that the 'point' of an empirical geometry is infinitely small space, also the spherical locus *generated by its movement* is a small space. Every spherical locus completely encloses a finite space comprising the fixed point or centre. The finite space enclosed in a spherical locus is a sphere (*Kugel*). The space between two concentric spherical loci is called a spherical 'peel' (*Kugelschale*). Every spatial form that pertains to the sphere is its *inner form*; every spatial form that does not pertain to it is its *outer form*. The *outermost* element of a spatial form is its *boundary* (*Grenze*).

In an empirical geometry of perceptual space, therefore, a boundary *cannot* be something *stable* (because in that case it would still be divisible into an outer and an inner form because of the infinite divisibility of space). It is an aspect, and precisely that *where* the object ends, and can only be an '*indefinitely small part*' in the sense defined above. Every spherical locus is the *outermost element* of the *enclosing sphere*.

These considerations yield the following consequences:

1. Every spherical locus is the *boundary* of a sphere.
2. Every spherical locus is a *surface*.
3. A surface is the *boundary of a body*.

Thus the concept of *boundary* which, as the *outermost* element, *identifies a perceptive form* is the *fundamental fact* about phenomenal space. Points and lines that delimit a surface are, in fact, examples of the bounding of perceptive

space. Moreover, boundaries are never given in isolation, they are always part of larger spatial forms (Brentano, 1976/1988). Boundaries, then, have an *inner* and an *outer* side, as it is evidenced, for example, in the phenomena relative to figure/ground organisation in perception (Palmer, 1999: 280ff, esp.: 286–287; Albertazzi, this volume).

7. Canon

Against this philosophical background, it is evident that formulation of a theory of intentional reference on an empirical basis must necessarily draw upon the results of analyses conducted in the spatio-temporal continuum of the perceptive fields of vision, hearing, touch, smell, and kinaesthesia. Accordingly, this book presents a series of scientific analyses intended to identify the characteristics of, in particular, the objects of touch, vision and hearing, and the forms of their perceptive organisation. The essays that follow, in fact, variously underline the different characteristics of continua, like direction, velocity, boundaries, etc. in the various perceptual fields.

From the foregoing discussion it also seems that we may conclude, at least in the first instance, that a *psycho-physical* continuum theory is only conceivable if also the presence of its *intrinsically subjective* and *operational characters* is considered.

Consequently, new paths open up for research, in a series of successive by-forcations. Firstly, there is the *heuristic* problem of reconstructing the *origin* of the continuum in vision, in sound, in touch, in the kinaesthesis and in the inter-modal perception in a sort of pre-geometrical approach, and of its *description* (see, for example, Crapo and Rota, 1970). It is the intention of this book to constitute a first approach to this theme, and in exactly these terms.

Secondly, there is the problem of a possible *formalisation* of the continuum. Before confronting this task, however, it should be remembered that the perceptual continuum always exhibits two aspects:

1. One closely connected to the *structure* and to the *morphogenesis* of the various forms or '*objects*' appearing in the various perceptual fields: an aspect which relates to the first of the above mentioned problems (i.e., strictly speaking, of the *contents* of perceptions).
2. The other is more directly connected to what, if we follow a linear order, we can call the '*conceptual-representational*' aspects of the continuum itself; an aspect which relates to the second problem (i.e., reference through

operations of abstraction and idealisation to other types of '*objects*' as, for example, punctual 'instants').

It is advisable, however, to bear in mind that in the second case we have already gone *beyond actual perception* (that is beyond perception of the spatio-temporal moment-now, of the *boundary* of the temporal continuum). We should bear in mind that the *theories* of the continuum assembled here are only *epistemological constructs*, resulting from a series of abstractions and idealisations, which enable us to configure the continuum as a *whole*, analogously with the introduction of the sign ∞ in mathematics.

Finally, *from a philosophical point of view*, a theory of the continuum takes shape like the *theory of the unfolding of the actual direct reference* in a *continuum and successive architecture of cognitive integrations*, which takes us to some sort of moderate constructivism, albeit on realistic bases.

All that we are able to 'say' about reality, at a '*representative*' level, in fact, is solely the result of a series of *cognitive integrations* to an extended construct which seeks both to 'run through again' and to 'anticipate' the *unity* of the *various phases of continuum* starting from the '*actual presentation*' of the moment-now.

Acknowledgments

This book arises from events organised in Bolzano, Italy, by the *Istituto Mitteleuropeo di Cultura/Mitteleuropäisches Kulturinstitut* (recently established as *Mitteleuropa Foundation*) as part of the *International Schools in Cognitive Analysis* (scientific board: L. Albertazzi, R. Langacker, J. Petitot, R. Poli, and L. Talmy). In particular, the essays collected in the book deal with the themes addressed by the school *Unfolding perceptual continua* held in September 1998. I wish to thank the President of the Institute for the support that he provided for these initiatives.

I also take the opportunity to thank J.J. Koenderink, R. Poli and G.B. Vicario for our discussions about space, time and continua. A special thanks to O. Da Pos for his punctilious reading of the text.

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CHAPTER 1

Towards a neo-Aristotelian theory of continua

Elements of an empirical geometry[1]

Liliana Albertazzi

> Definition: we call *locus what is modified in motion*. (F. Ueberweg, *Die Prinzipien der Geometrie, wissenschaftliche dargestellt*)
>
> Finally, the visual impression will be totally reduced so as to set the visual focus to a single point; at that point the seer will take account of the spatial relation of the various points with the movement of the eye. At this stage one may say that he has transformed seeing into a real touching and into a movement, and the presentations based on this are no longer presentations of visual impressions (or in short, visual impressions) but presentations of movements which constitute the material of vision and of the presentation of form. (A. von Hildebrand, *Das Problem der Form*)
>
> We are led in this way to consider a very different world view from that which is behind classical physics. In this view, there is no ultimate set of separately existent entities, out of which all is supposed to be constituted. Rather, unbroken and undivided movement is taken as a primary notion. Or, equivalently, we can say: *What* is, is a whole movement, in which each aspect flows into and merges with all other aspects. (D. Bohm, *On creativity*)

1. Perceptual continua

One of the problems raised by contemporary research in AI, and in particular by naïve physics (McCloskey et al., 1980; McCloskey, 1983; Hayes 1985a, 1985b; Hobbs and Moore, 1985; Allen and Hayes, 1985), is clarification of the nature of *space–time continua*; clarification which requires, at various levels, revision of the *base primitives* (point, line, surface, body, boundary, direction, velocity, etc.) of *perceptual* objects, and consequently revision of *conceptual categories* and *relations* (like place, distance, position, change, before–after, etc.). These theories have again proposed a conception of the world which often displays the features of Aristotelian physics, and for the formalisation

of which set–theoretical logical–formal tools have generally been used (see Introduction).

The Aristotelian conception of physics, however, is based on primitives and conceptual categories different from those described by modern physics; primitives and categories which also differ from those employed to develop the formalisms available to us today. For example, *movement* plays a prime role in the Aristotelian conception of perceptive continua, but this is not the objective movement of the laws of classical physics but rather the real *perceptive phenomenon* of movement as it appears in the various perceptual fields, in the change of *place* by objects, or even in cases of *apparent* movements (see again Introduction).

The Aristotelian theory of continua springs from a conception which subsequently considers those *aspects of phenomenal experience* which yield the intuitive concepts of *consecutive*, *continguous* and *continuous*. Precisely:

1. "consecutive [...] is that which does not present any intermediate of the same kind between itself and what is consecutive to it." (*Physics*, V:3, 227a:1);
2. "contiguous [...] is that which, besides being consecutive, is also in contact." (*Physics*, V:3, 227a, 6);
3. "continuous [...] is a particular determination of the contiguous [...] when the limits of two things, by means of which the one and the other touch, become one alone [...]." (*Physics*, V:3, 227a:11–12).

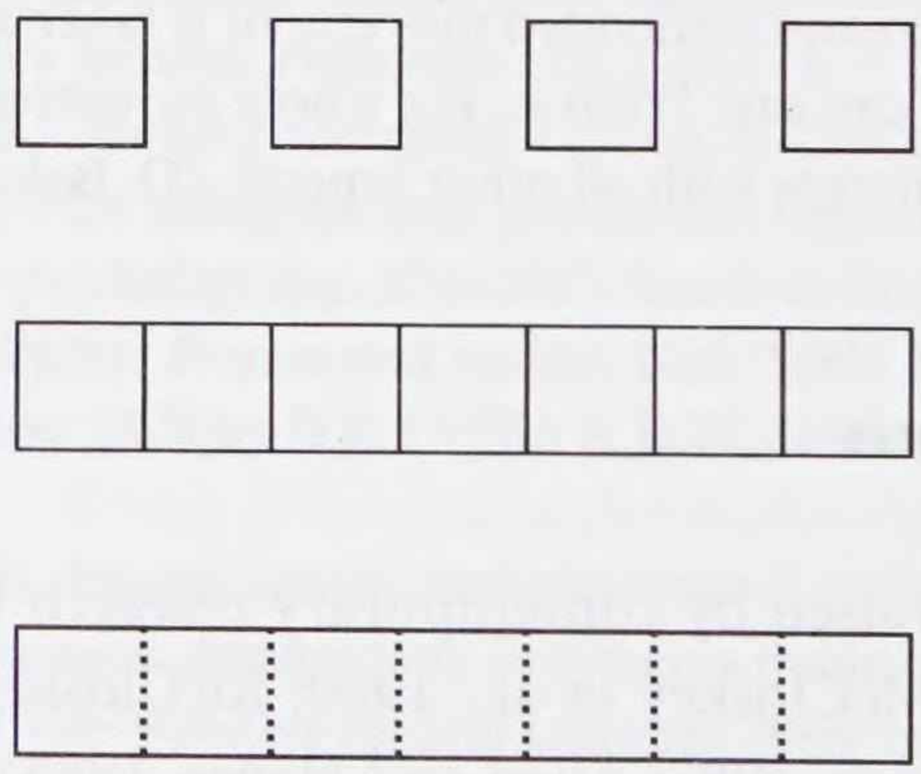

Figure 1.

Note that, for Aristotle, in the case of *two contiguous objects which become one continuous object*, the boundary between the objects *belongs to both of them*. That is to say, there is a *coincidence of boundaries*; and this is a concept which conflicts with that of 'approximation' in the mathematical continuum.

Besides the three types just outlined (consecutiveness, contiguity, continuity), in other passages Aristotle adds a further characteristic: that of the *solidarity*, which comes about when *the parts move in the same direction as the whole*, an example being a rotating disk (Ueberweg, 1851; see Introduction, and below).

In modern times, a neo-Aristotelian theory of continua is apparent in various forms, in the works of those authors (mainly of German culture) who have evidenced the *grounding of continua in the world of perception* (Herbart, 1806/1908; Ueberweg, 1851; Lipps, 1897; Brentano, 1976/1988; Husserl, 1983; Bühler, 1913; Selz, 1929; Musatti, 1926; von Allesch, 1931; James, 1980. See Introduction). The following discussion is largely based on these works, and on analysis (descriptive and also experimental) of perceptive phenomena which exemplify their theories (specific references to the theories of the various authors are given in brackets).

One point of departure also for these theories is *analysis of the movement* of a body in space. Studies of the simple experience of movement by a body yields the basic 'definitions' for an empirical geometry (not yet Euclidean) which constitutes the preliminary foundation for every successive possible mathematical-formal development (for mathematical exemplification of this conception see Helmholtz, 1867, and Lie, 1890. On these aspects see Robb, 1921. More in general, see Torretti, 1978).

The various above-mentioned theories have a number of features in common, although they do not always draw a clear distinction between the *physical* and the *perceptive* type of continuum: this, however, is an *ontological* ambiguity which is common to all the discussions about continua (also mathematical ones) conducted between the end of nineteenth century and the beginning of the twentieth (see Introduction). More in general, at issue were the nature and the laws of *psycho-physics*, which provided the basis for the notion of continuum, a question which is still unresolved.

However, one thing is clear regarding all these theories: they are *not*, in any way, *mathematical* analyses of continua. At least, they are not so yet. In fact, it is only subsequently, by *idealising* the data offered by the senses, that one can apply to empirical perception the axiom, or assumption, that the properties *identified* and *described* from a perceptive point of view are *compatible with a model*. Against this background, in what follows I shall present some elementary concepts preliminary to a theory of perceptual continua, taking account of both the phenomenological and the Gestalt analyses of perception.

An important point to bear in mind is that the following discussion is mainly concerned with the *morphogenesis* of perception in *actual duration* (on

the relevance of the moment-now for the theory, see Introduction. For an experimental analysis of this aspect see Palmer, 1999: Ch. 6). Consequently, my analysis will not deal here with phenomena concerning the memory or the more specific 'mental' processes based, for example, on comparison, inferences, etc. Nor will phenomena of the transportation of images at mental level be considered, given that they pertain to a higher order level of presentation (on this see, amongst others, Shepard, 1982; Cooper and Shepard, 1978, 1984; Kosslyn, 1980; Finke, 1989; Tye, 1991). Discussion of the neurophysiological aspects of perception will also be omitted, since my treatment will be restricted to the *phenomenic level of appearances* in the perceptual field. As a consequence, also some preliminary stages of the genesis of perceptual appearances, at the level of *constructional routes* based on the processing of signals, will have to be set aside (see Kolers, 1972).

A second important point is that my analysis will concentrate mainly on aspects of perceptual *space* and *time* continua (mainly space). It will not deal specifically with, for example, the inner complexity of individual perceptual fields like colour, touch, sound, etc.; although, as we shall see, space and time in this ambit of reality are never given independently from the 'objects' that appear in the various perceptual fields (These matters are addressed by the other contributors to the volume. For a first approach to the problem of a perceptual time continuum see Albertazzi, 1998a, 1998b, 1999a). Again, as already noted, my enquiry will be concerned with to the *phenomenic stage* of the processing of perceptual appearances.

2. Room for movement

An important point to make clear is that the spatial *extendedness* (*Extensität*) of a perceptual object is not immediately the *extension* (*Ausdehnung*) of classical geometry: the two concepts belong, in fact, to two different fields of analyses. The use of the term 'extendedness' therefore serves to prevent the importation into the theory of inappropriate contents that might call some kind of formal geometry to mind (see Lockwood, 1989).

The difference between the concepts of 'perceptual extendedness' and 'extension' can be showed by considering the simple but striking fact that in the visual field the perceptive evaluation of the *empty* distance between two points differs from the evaluation of a *straight* line drawn between two points, and also from the evaluation of the size, or better the *thickness*, of the two limit points, given that when a point has thickness it also acquires a *ground*. Of the

same type are assimilative phenomena, like the fact that, if a square is placed between two squares both larger than it, and if it is then placed between two squares equally smaller than it, the squares appear to be smaller in the first case than in the second. A simpler example is the fact that the distance between two connected points appear shorter than between two unconnected ones (already in Lipps, 1897; see also Scholz, 1924).

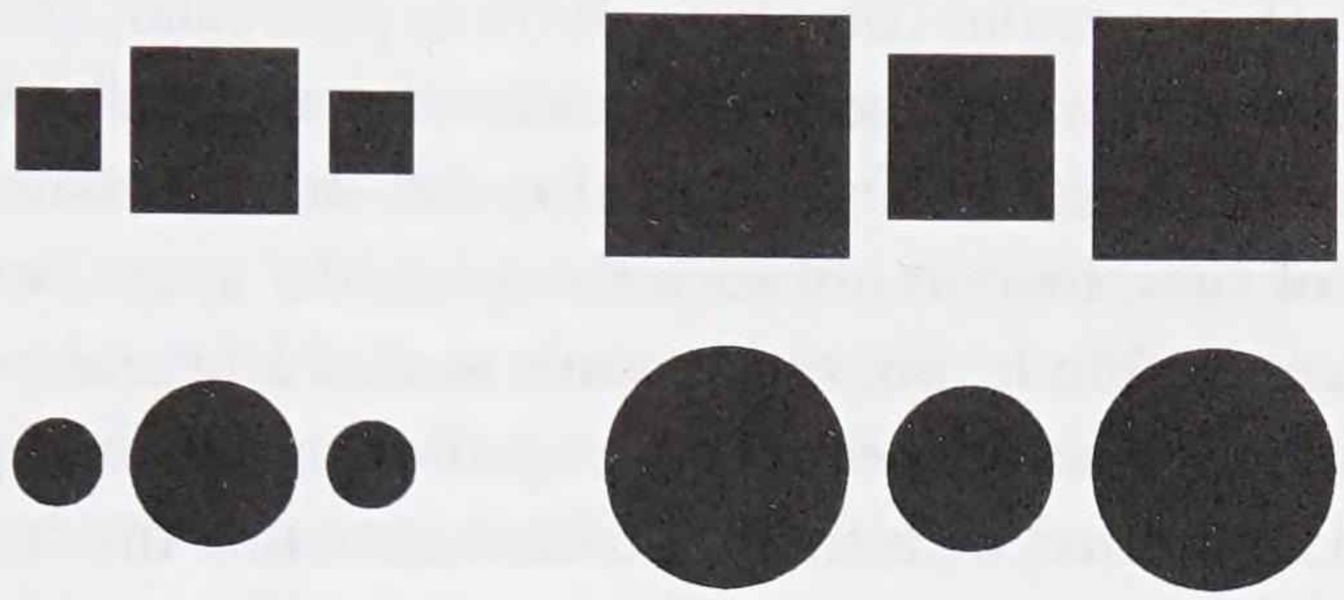

Figure 2.

Something very similar provoked the controversy between Leibniz and Newton on the nature of space (Jammer, 1954: Ch. 4).

At a more complex level, perceptions like the optic–geometrical illusions, stereokinetic phenomena, phenomena of amodal perception like Kanizsa's triangle, transparency phenomena, etc., are all examples of the extendedness of perceptual 'objects.' These phenomena show the *intrinsecally cognitive* nature of perceptual space, in which forms of subjective completion are at work (Albertazzi, 1995, 2001a). To recall a conclusion arising from Lipps' theory of space – which is based on a painstaking analysis of the nature of optical illusions – in the realm of perception even 'particulars' like points, lines and surfaces, and more generally spatial configurations are bearers of a certain *behaviour* and are part of a field of *psycho-physical forces to which empathic, meaningful cognitive traits* also belong (Lipps, 1897; Albertazzi, 1998b).

From this point of view, when analysing the continuum one should bear various distinctions in mind, concerning, for example:

1. the domain of perceptual objects, which can be labelled as the 'realm of ecological perception' (Gibson, 1979);
2. the type of subjective integration which variously intervene in the final rendering of the perceptual 'object,' at the level of the primary process as well (Benussi, 1923==5; on Benussi see Albertazzi, 2001b);
3. the evolutionary contribution to percept-configuration (Riedl, 1988).

Extendedness is a general feature of all actual perceptive phenomena, not only of 'odd perceptions.' One of the principal characteristics of extendedness is the fact that, at the phenomenic level, it is always endowed, or 'filled' with *sensory modalities* like colour, sound and touch (the question is even more complex with regard to taste and olfaction). For example, there is some sort of bilateral dependence between *figural form* and *perceptive content* so that there is no extendedness without colour. More in general, perception is given by *qualities* in a *space of senses* (*Sinnesraum*) (Brentano, 1907: in particular, 164–175).

From this point of view, the constitution of perceptual objects proceeds jointly with the constitution of perceptual space. In other words, from a descriptive point of view, there is not such things as '*the*' space, and then points, lines and surfaces 'within it,' but rather some sort of *bilateral synergy* between them in a duration, as the former example on the evaluation of points shows.

A problem connected with the last consideration is the fact that, strictly speaking, in actual duration we present *qualities*, like nuances of colours, sounds, etc.; but we do not yet immediately perceive *objects*, of which the previous are potential precursors. At issue, then, is the nature itself of perceptual space as the *primitive location* and *individuation* of perceptual objects (see Introduction). An important aspect of the theory therefore is how we can connect the continuity of successive perceptual aspects of, for example, seeing, like seeing something *yellow*, seeing something *quadrangular*, seeing something *high* with seeing an 'object' of a certain type, say, seeing '*a house*.' However crudely put, this is in synthesis Husserl's theory of the noematic aspects (*Abschattungen*) of phenomenic objects (Husserl, 1900/1, 1913, I; Albertazzi, 1989, 1998a. These problems are of close concern to AI. See, for example, Adelson, 1978).

Indeed, what we *present* to ourselves *directly* (as Brentano and Husserl, for example, contend), in the case of a spatial relation, is only a *un-qualified place*, from which whatever is coloured, for example, is intuited as *being distant* to a certain *degree* and in a given *direction* from this location (Brentano, 1976; Husserl, 1983). This place functions as a *general place* wherein *to locate* the qualifications arising from the different sensorial fields, like something *coloured*, or something *resonant*, or something *coarse*. In other words, *intrinsically belonging to the perception of an object is the position of the self*, as the centre of relation of all the spatial apprehensions successively apprehended within the actual duration. This entails that perceptual space is essentially a 'room for movement' based on proprioception related to the observer (for a recent analysis of the characteristics of perceptual space and its indexes for depth see Cutting, 1986; Cutting and Vishton, 1995).

As regards sight, for example, the *dynamic* phenomena of the visual field – intrinsically connected with the cognitive operations – and dependent on both oculomotor and kinaesthetic behaviour – are from a phenomenological point of view substantially three in number (Husserl, 1988):

1. dislocation through *sliding* (*Verschiebung*);
2. distending through *stretching* (*Dehnung*);
3. partial or total *covering* (*Deckung*).

1. In the visual field, *dislocation through sliding* comes about when, with simple *ocular movement*, I am able to see, maintain and/or dislocate the aspect of a seen object (e.g., a table) from the centre of the visual field to the background, rightwards, upwards or downwards, etc. As far as the visual field is concerned, the dislocations of aspects, and their *locations* are due essentially to ocular movement and to the shift in the body's position. The relation between *space* and *location*, then, is one of the main point to clarify in a theory of perceptual continua, given that phenomena are dynamic in character.

Dislocation is the mere *change of place* of an aspect, without change of magnitude or orientation. In dislocation, what is dislocated is the aspect itself, and only the *co-ordinates* of the kinaesthetic circumstances are altered. In fact, the elapsing of the kinaesthetic circumstances is the *condition* for the passage from one oculo-motor aspect to another, so that the aspect does not undergo any 'internal' change (which holds only for ocular movement, however).

2. An example of *distending* in the perceptual field arises if I move rather than keeping still, so that, *because of my bodily movement*, the aspect of the object undergoes a *distending due to stretching*. Distending, then, it should be noted, is always *relative to the point-Me*.

Distending in the visual field involves a *change* in the aspect due to kinaesthetic movement (from right to left, in height and width) and the consequent *modification of its distancing* by means of stretching in the field.

To summarise, distending is a change of orientation and a change in the distancing of the aspect. Distending, contrary to dislocation, involves the *magnitude* of the aspect: it may be positive or negative, of *extending* or *shrinking*. Examples are to be found, for example, in both the literature on the arts – in Ruskin for example (Ruskin, 1857) – and in the literature on 'scale space' in computer vision (Koenderink, 1993); which confirms the importance of the problem from a variety of viewpoints, i.e., those concerned with visual, sensorial and pictorial representation. In philosophical terms, the latter is an aspect

of the particular theory of continua known as the 'theory of intensive and/or extensive qualities' (for Brentano's view see Brentano, 1907).

Distending pertains both to the *form* and the *qualitative content* of the thing: for example, if I see a table, on approaching it I see it as larger, if I distance myself from it I see it as smaller, and the colour itself may undergo changes. Example of the nature of the 'optic flow' in the modern scientific literature abound, and obviously in Gibson's theory of vision (Gibson, 1979: Ch. 5).

Finally, distending permits the transport of one aspect onto another, relatively to ocular movement and kinaesthetic movement (see also Lipps, 1897). Every transport of an aspect synthesises, merges or fuses it with the previous one, until a *multi-faceted unitary perceptive object* is formed: a construction put forward by both, Husserl and Gibson. Indeed, the point is the source of the notion of Husserlian 'noema,' a cornerstone of the phenomenological theory; and it also correspond to Gibsonian 'vistas' (Husserl, 1913, vol. I, 1966a; Gibson, 1957; 1979: 132–134, 195–196, 198–200).

From this point of view, distending is also at the basis of the *constitution of a three-dimensional space* through the transport of the oculomotor field into a multiplicity of distendings and dislocations which operate on the basis of the cognition of the *identity* of the objects perceived, despite their change of form. The phenomenological description of both qualitative and quantitative change in visual perception is, once again, rather 'Gibsonian.'

In fact, the different positions of the forms of objects in the perceptive process are cognised as 'causally' connected, and as 'temporally originating' from a single initial position: a point on the optical flow today shared by computer vision theory. This initial position, in its turn, is assumed on the basis of an *inferred* corresponding *fixed position* in the *physical* continuum.

The importance of this aspect is owing to the fact that perception of causality is a *feature* of the *structure of consciousness* (Husserl, 1966a). The process is therefore twofold: the structure of the intentional reference in the actual perception enables the constitution of an *inner order of positions of the successive aspects of the object*, while at the same time it maintains the *simultaneity* of the *successive order* of these different positions, linking them to an originary moment which started the process when triggered by external stimuli in the physical world (Husserl, 1996a, 1966b, 1988. For the theory of intentional reference see Introduction).

3. Finally, *covering* consists in the *masking* of one aspect by another aspect which conceals, covers, impedes it, etc. Covering occurs whenever an aspect moves in the visual field so that it becomes, partly or wholly, *non visible*: that is,

when one aspect covers, masks, occludes and impedes the view of another (for a classic analysis of these phenomena see Gottschaldt, 1926). Covering phenomena in everyday experience are exemplified by a house which covers the vista of a landscape – but also a house which covers itself! – a man hidden by a hedge of a wall, a car that speeds among houses, a hare that runs behind trees, etc.

The covering may be partial or total, when complete *coincidence* or overlapping occurs, as in the case of two identical squares. In covering, however, the aspect maintains its *identity* and *integrity*, even if it is *partly occluded* or *occluding*. This, in fact, only happens if one sees the occluding item *as well*, and not just the individual parts, a good example being provided by the fact that in music perception, in order to perceive a melody, one must also have an occluder (in this case, noises) (Bregman, 1977, 1978, 1994).

An experimental example of covering and continuity phenomena is the *tunnel* effect, analysed by Burke, Knops, Sampaio et al., members of the Louvain School (Burke, 1952; Knops, 1947; Thinès et al., 1991: 152). What happens in this case is that the observer 'perceives' the *object* observed as *continuing its movement behind the obstacle* (which is a case of permanence of anteriority and/or posteriority of objects. See below, §3).

The experiment consists in presenting subjects with *two successive movements* of *similar objects situated on the same plane* but structured in such a way that *the end of the first movement* and *the beginning of the second are covered by a screen*. A small screen (of 1 or 2 cm) is placed in the centre of the slit to form a tunnel. Then, a moving object (for example, a rectangle 5 × 8 cm) is sent across the slit.

Under certain conditions of velocity and direction of movement (30 to 60 cm/sec), the impression gained is that of the *continuous and uniform movement* of the object passing behind a screen. The hidden *phase of movement* assumes all the characteristics of a *visible, real movement*, where, by 'real' movement is intended a movement which is effectively perceived (it is an open question whether repetition plays any role in this effect). A *temporal prolongation* of the duration of the non-visible phase invariably translates into the impression of a *momentary halt* behind the screen (Vicario, 1991; see also below, §3).

The screen experiment also sheds light on the role played by the so-called *unilateral functions of the margins* (according to the law of segmentation of the perceptual field into figure/ground): in fact, the margin is attributed to the figure (Koffka, 1935. On segmentation from an experimental point of view – both boundary-based and region-based – see Palmer, 1999: Ch. 6, 268).

The concepts of the dislocation, distending, and covering of perceptive space have a role to play in a descriptive theory of perceptual continua. They

make it possible to overcome, at least in the first instance, the problem of the perception of mere disconnected qualities. These dynamics internal to the visual field, which transform images by synthesising successive aspects or perspective point of views, construct a unitary perceptive 'object.'

This step, moreover, is made possible only by the passage from analysis of apparently unconnected individual '*moments-now*' of perception to the merging of different aspects or perspectives into the various perceptive temporal *phases* of *simultaneous* perceiving. In other words, it enabled by analysis of the *temporal continuum of perceiving*.

From this point of view, one *characteristic* of *perceptual space* is the fact that *space* and *time* continua are *interwoven*. *Spatial perception* consists of a *superimposition* on *temporal perception*, since a perceptual object *has* its time, *extends* in time and *fills up* time (see below, §7. The same position is to be found in Lie's groups as an example of continuum in geometry).

In this case too, the focus of the theory of perceptual continua is on the *subjective operations* active in the presentation of spatial perceptual objects. In illustration of this point let us take a simple example. Image a green disc in front of you:

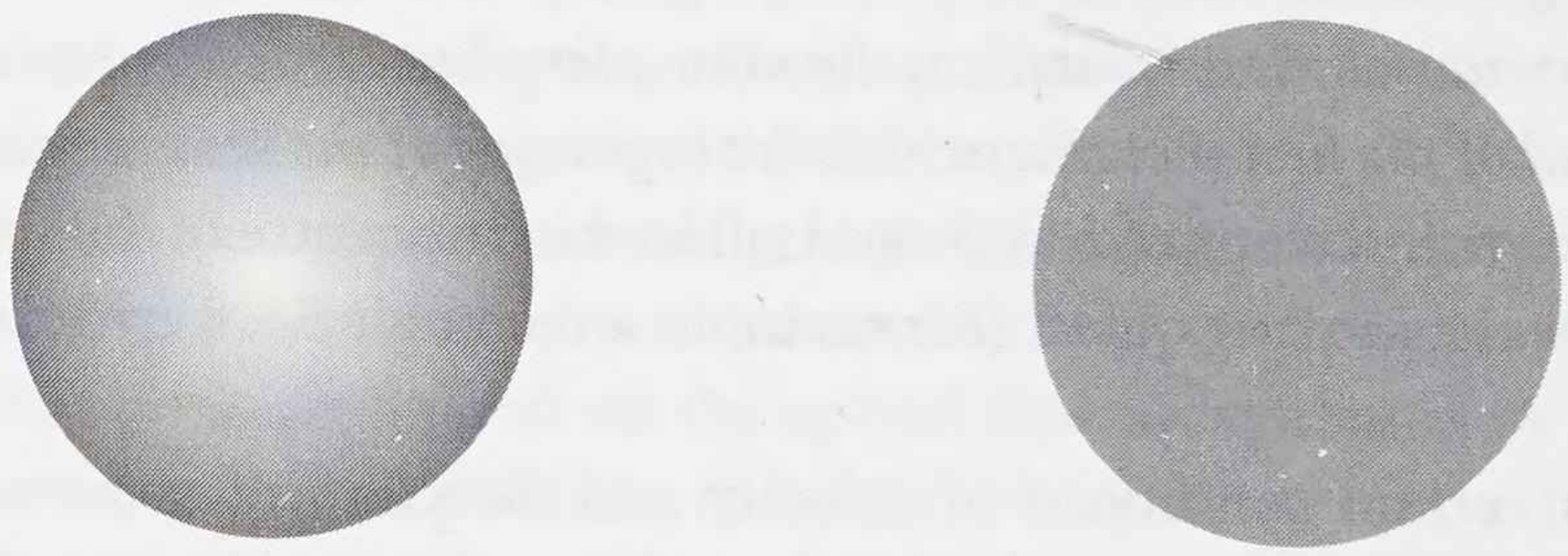

Figure 3.

What we see is a *coloured disc*, even if we are presented only with *one perspective aspect* of it, the *frontal* one, whose first visualisation offers a *concordant filling*, i.e., a sphere filled with colour, etc. As usual, perception *fills all the missing perspectival data* (for example the disc's rear) of the different aspects of the object (a similar example is to be found in Poincaré).

Subsequently, however, when *walking* around or when *rotating* the object, *part of the rear*, which was previously not visible, is made manifest. Now we see a *different* perspective aspect of the object (say, a grey rear). This new aspect now *joins* and *overlaps* and *fuses* with the aspect of '*coloured disc*,' which is now lost. After the different sides of the object have been seen, the *entire meaning* of the whole perception changes, and not solely that which pertains

to the *actual perceptive stretch* (on the dynamics of the moment-now see Benussi, 1913; Husserl, 1966a; Albertazzi, 1999a). In fact, the modification of the aspect *radiates back* towards the *past* perception, towards the totality of its *previous* appearances which underlies the *temporal structure* of visual perception. The whole aspect of an object, then, is *not* made up of *only a one-sided perceptive stratum*: it has also a *functional* nature, *pointing at* the possible connected aspects of the object under observation (Husserl, 1983).

Generally speaking, in order to perceive a *solid* object, it must be delimited by surfaces which are not all directly visible, but partially *amodally* perceived, as experimentally showed by Tampieri (Tampieri, 1956).

The perceptual analysis of the construction of the object in the phases of an actual duration thus specifies the nature of the *pointed-to* (or intentional) *object*, which acquires a sort of *ontological status per se*, i.e., it is:

1. what is *actually perceived* in acts of seeing, of hearing, of touching, etc.;
2. exactly *in the way in which it appears* under certain *field conditions* of light, perspective, distance, motion, stasis, etc.;
3. connected but *not reducible* to the physical stimulus(i) which triggers it (which, by the way, is the origin of the concept of *Bild* widely used in twentieth-century epistemology).

Immediately given with *that* particular perspective of the perceived object, *all its other aspects,* however invisible, are *co-given* as *correlated* and necessarily *connected* aspects of that *type* of object. This holds even in the case of a disappointment or an unexpected surprise, as in the above mentioned case. Circling around the object, or rotating it, by means of *a series of kinaesthetic movements*, serves in fact to confirm or gainsay, totally or in part, our anticipations. On this basis, perceptive objects, rather than being separate from each other, seem to establish themselves as *patterns of movement* (see Bohm, 1998).

3. Perceptive objects

Generally speaking, perceptive objects display characteristics of *pre-existence*, *permanence* and *continuity*. I shall illustrate this point with some examples.

The first example is known as Boltzmann's *Schubladexperiment* (Blackmore 1995/6, vol. 2: 153). The question is as follows: if we put an object in a drawer and close it so that we *cannot see* the object, has the object really disappeared? We then open the drawer, see the object again and conclude that the object is there and probably *continued to exist* when we could not see it.

Briefly, the *Schubladenxperiment* shows that *if there is an interval* during which the stimulation of a sense organ is interrupted, the interval may be *'perceptually' filled*. More in general, the optical system always fills gaps and goes beyond the information given by means of *perceptive interpolation* (Kanizsa, 1980). This happens also in the case of the fleeting objects of Meinongian ontology, like flashes in the dark or shots in sound space, where the problem is understanding how consciousness is able to individuate these as 'objects' of some type (on this topic see Albertazzi, 1996). The tendency towards 'conservation' or minimal change is evidenced at the phenomenal level by the fact that a *temporarily* invisible object does not cease being experienced as existent. The tendency to interpret particular interruptions and changes of the objects of perception as characteristics of our *participation* in the world is well illustrated by Duncker (see Duncker, 1947: 537).

Another case of *phenomenic continuity* is the one already mentioned in which the *sudden appearance of an object* in the perceptive field (or its disappearance), arouses the impression that the object *pre-existed*, and then has simply been made *visible*. It is an evident phenomenon occurring when an image appears on a computer screen in power point: it seems to *enter* the screen and being *pre-existent*. This phenomenon is a constant occurrence in everyday experience, for example when a rabbit suddenly runs across a field and disappears: we experience the rabbit's pre-existence, and when it has disappeared, our impression is that it continues to exist and that it is simply hidden.

A group of experiments concerning phenomenic *permanence* (anteriority or posteriority as well) and correlated with phenomena of *sliding* in the case of perceptual objects were conducted by Michotte of the Louvain school. I present the *screen effect* on the phenomenic permanence and sliding of objects in Vicario's version (Vicario, 1991: 214; Knops, 1947; Michotte, 1954; Michotte et al., 1962. See also below, §6):

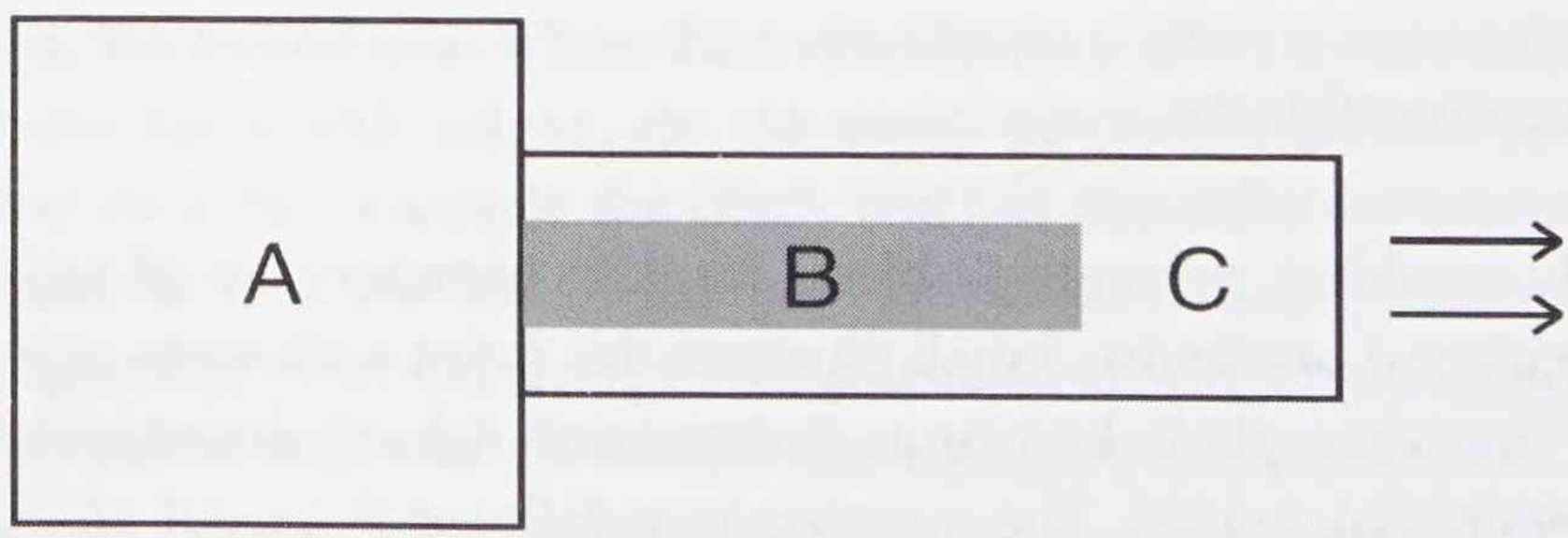

Figure 4.

Take a square A and a white rectangle to the right of A.

First, only A is projected uniformly onto a white screen, while a device C in the projector hides B.

C is then moved rightwards so that contiguous parts of B can be seen appearing on the screen.

Under certain conditions of *velocity of movement*, *relative magnitude* and difference of clarity, one does not see a square A, and a rectangle which extends and dilates rightwards, but rather an *object* of indefinite but constant length which *emerges, sliding from behind* and progressively revealing some of its previously hidden parts. Which means that the object A *takes on* the function of a screen. Recall that 'sliding' is a feature of spatio-temporal extendedness (see above, §2).

The experiment also shows that the masked object has not only spatial but also temporal extendedness in the past, since we gain the impression that it has been already present (Michotte et al., 1962: 368). That experiment therefore highlights another important aspect of the role played by spatial and temporal *boundaries* in perception.

Other experiments conducted by Michotte and researchers belonging to the Louvain School concern the *phenomenal existence* of the *causal nexuses* among perceptive events: one of the principal tenets of an experimental phenomenology (Michotte et al., 1962; Thinès, 1977; Albertazzi, 1998a).

Michotte shows that perception of causality is not a *physical* phenomenon, determined, for example, by the *physical contact* between two billiard balls where one *knocks into* the other.

We indeed *perceive causality*, and also *continuity* in the perceptual fields, although strictly speaking, *from a physical point of view* they do *not* exist.

The causal relationship is *directly experienced* also in the case where two figures (for example two small squares) projected onto a screen *move* in a *certain way* according to a *certain velocity* and *direction*: and precisely when one figure starts to move at the same moment as it is reached by the other.

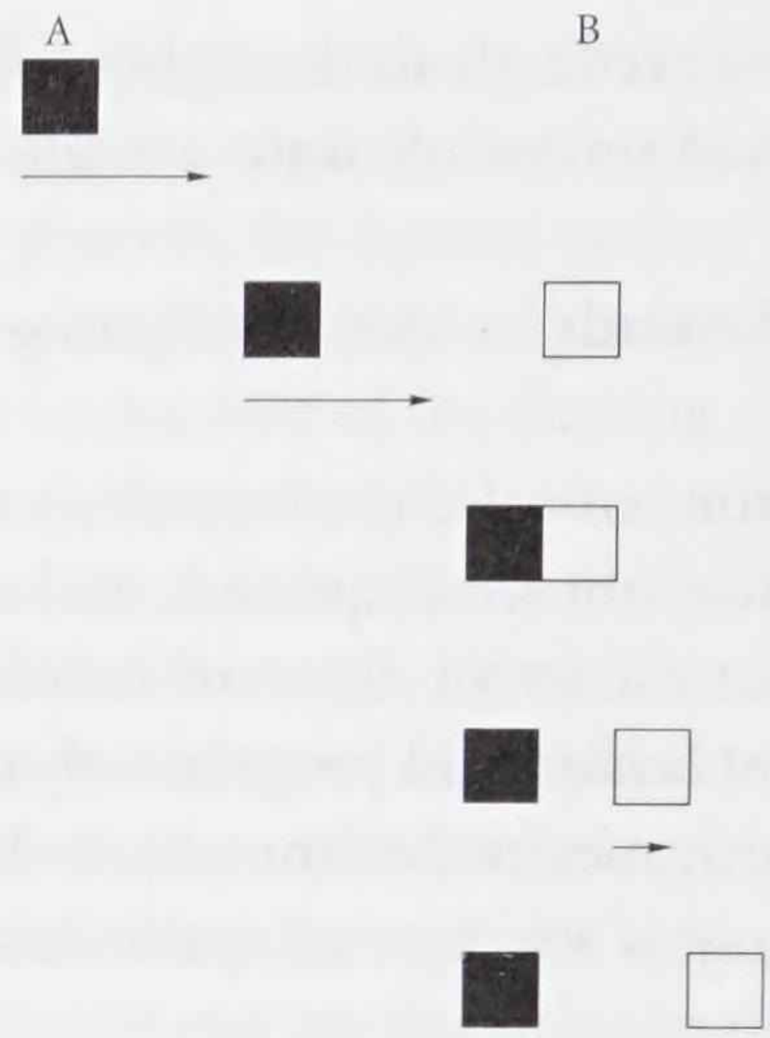

Figure 5.

Take a small square A which follows a horizontal trajectory at high speed (36 cm/sec) and stops when it comes into contact with small square B. After 20 msec, B moves along a trajectory which is a prolongation of A's, but at a much slower speed (8 cm/sec). After only 4 cm (500 msec), B comes to a halt. What is perceived is a sort of 'launch effect' where the movement of B is *caused* by A, although from a physical point of view the two movements are *independent*.

Moreover, variations of velocities and of temporal distances between the two movements give rise to the *perceptual renderings* termed the *jump* effect, the *unhooking* effect, and others (see also below, §6). That is to say, we *see* different perceptual objects (or events: in this case movements of a certain type) which are *qualitatively* different.

In this case too, *spatial perception* is closely connected with *temporal perception* (see below, §7).

Another variation on these experiments concerning the pre-existence of perceptual objects is the *gamma* effect which, from the point of view of the theory of continua, is an example of *pre-existence* of objects and of *distending by stretching*.

The gamma experiment concerns movements which are perceived in the field *without any corresponding movement* either in *physical reality* or in *stimulation of the retina*.

The gamma effect occurs when a darkened disc is *instantaneously* illuminated: the illumination is seen (perceived) to *propagate from the centre to the periphery* of the disc, i.e., not instantaneously with all the parts simultaneously

present. In other words, there is an *expansion* movement (much experimental analysis in this field has been conducted by Shimojo, see Shimojo et al., 1992, 1993; Nakayama and Shimojo, 1989; Hikosaka et al., 1991; Miyauchi et al., 1992; Murakami and Shimojo, 1992).

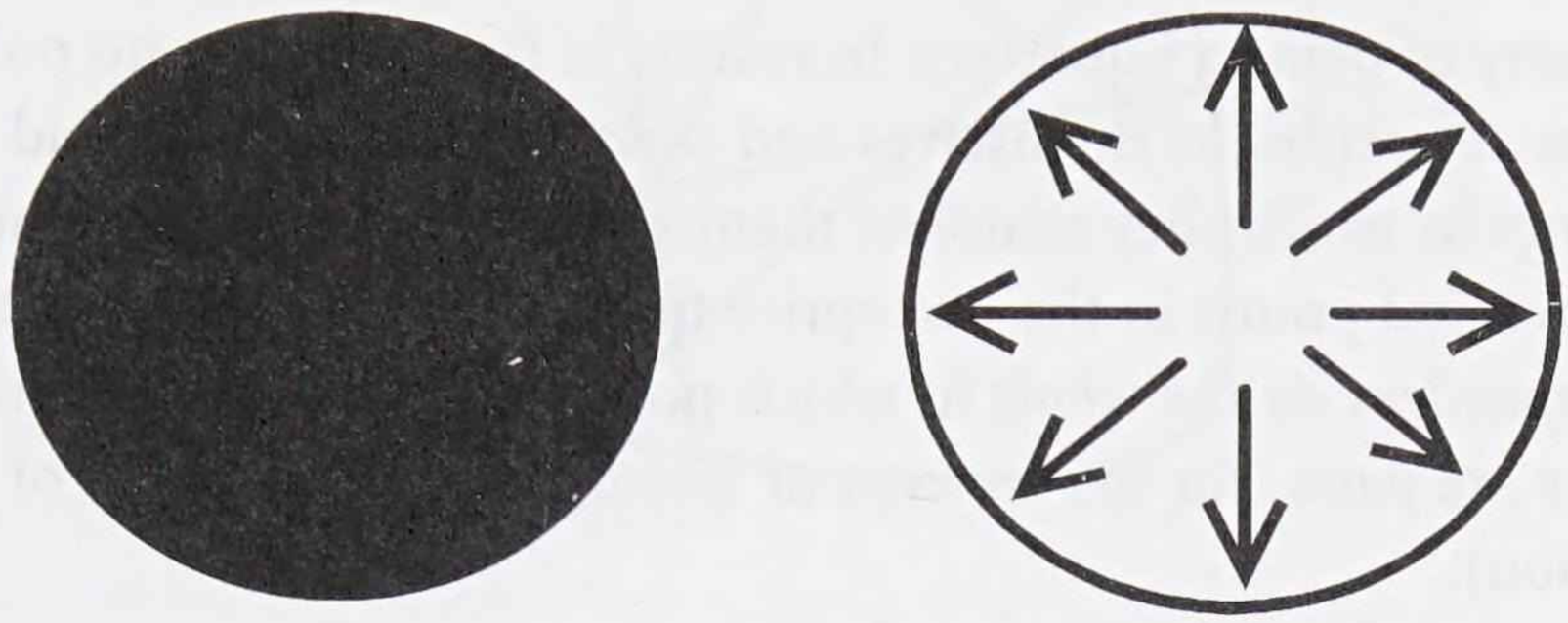

Figure 6.

The same occurs if the light is abruptly turned off. In this case the disc does not disappear instantaneously in all of its parts; rather, it disappears from the field *with a concentric movement* beginning from the periphery and ending at the centre. Which is another example of distending by stretching (see above, §2).

These observations should be useful for those setting out to devise formal tools with which to model the situation of spatio-temporal events. Attempts to formalise these structures using first-order logic, for example, have shown their intrinsic poverty.

The foregoing examples from the world of spatial perception point to a number of conclusions, given that they explain certain essential characteristics of the *primitive space location* of perceptual objects like *joining* modal phases together, *overlapping* different portions of space, making them *coincide*, etc.

In particular, they underline:

1. Some primitive *forms of synthesis* active in the perception of objects in the visual field.
2. The *non reducibility* of the phenomenic level to the physical one.
3. The intrinsic relation between *temporal* and *spatial continua* in perception.

All the examples provided so far, moreover, exhibit an intrinsic complexity. Is it possible to evade this complexity and come up with a systematic and an 'axiomatic' of perceptive continua?

From this point of view, it might be useful to try to define their *elementary characteristics* and then analyse the laws of organisation and increased complexity in actual phenomena.

4. Boundaries

The concept of *boundary* plays a key role in an empirical theory of *perceptual* continua. Perceptively, boundaries *never exist in isolation*. Moreover, a boundary is such *relatively to a certain context*, in which it acquires that specific property of being a boundary. In reality, in fact, there are no points, lines or surfaces as entities in themselves and *isolated from the field* and from the *surroundings* in which they manifest themselves. There is no absolute magnitude of lines and points in the perceptive field. There are only apparent magnitudes *dependent on the whole* in which points and lines are inserted and of which they are *parts* (for the concept of 'point,' 'lines' and 'parts' of space see Introduction).

Moreover, a boundary, even when continuous, can never exist *except as belonging to something continuous of more dimensions*, at least from only one side. Think of a beginning line:

Figure 7.

For example spatial points, temporal moments, moments of movement (as we saw in the case of perception of causality, above, §3) *cannot be totally separated* from something continuous. In other words, the only *existent whole* is the perceptual continuum as such, for no 'point' or 'instant' exist as whole (Brentano, 1976, 1933).

One of the main characteristics of the boundary of perceptual space is that it *divides*.

Boundaries can be *potential* and *actual*: for example, potential are all the boundaries of a surface before any point is drawn on it (an example being the lines in a marble block); or all the boundaries of a figure before it is drawn on a homogeneous blue surface, etc., as it happens in Seurat's painting.

Boundaries can be external and internal, as in the following figure:

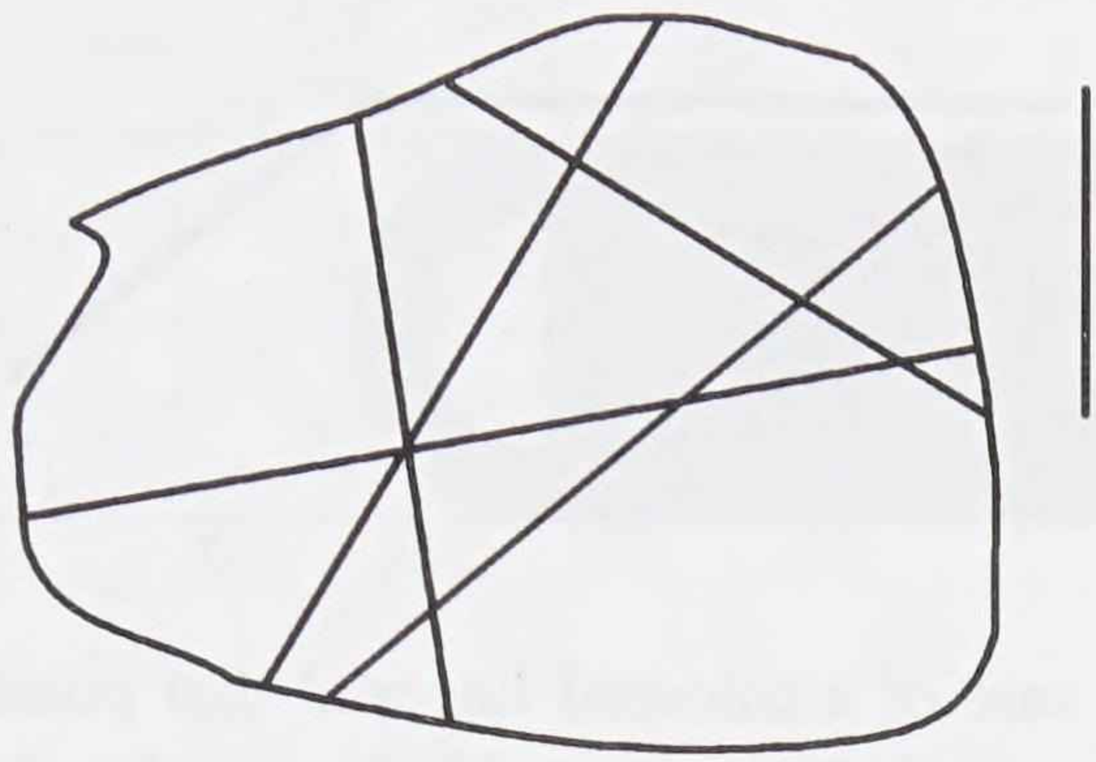

Figure 8.

In this case the internal boundaries divide the figure into different parts. Conversely, a segment placed near the figure is *not* a boundary at all: in fact, it is an open trace, which has been defined an 'object–sign' (Musatti, 1931; Massironi, 1982) (there is another type of boundary in perceptual space – as in the use of 'here' as opposed to 'there' – which does not pertain to any specific object: this is not considered here).

Boundaries play a major role in figure/ground organisation; but most interestingly they seem to play a double role in imparting shape to *regions* on both sides when, for example, holes are perceived (Palmer, 1999: 285).

Boundaries are *non-independent parts* of the continuum which *contain only certain directions* (for the concept of non-independent parts see Husserl, 1900/1901, Third Logical Investigation, and below). For example, a straight line contains all the positions or points that, with respect to a given point, show in a definite and constant direction and its contrary direction. If we reduce the extension of a line, we obtain a point. In the case of a straight line, then, boundaries belong to *both* the directions of the continuum.

Figure 9.

Also, the boundary between the two parts of a broken line does not consist of a sequence of points converging on a limit understood in a mathematical sense. For an empirical-experimental theory of continua, there is only *one point* in the line, which lies precisely between the two segments and belongs to both segments: there is, in other words, a *coincidence of boundaries*, because all the

incident parts have the same boundary (for a possible formal development of this perceptual fact see Prenowitz and Jantosciak, 1979).

Figure 10.

Now consider the case of a coloured line and that point in which the *line changes colour*, for example from grey to black: according to a neo-Aristotelian theory of continua, the point is both *grey and black* in the sense that a *coincidence of boundaries* occurs within it (what Brentano called a case of "plerosis through contact"). In fact, the point as such has no colour: it has the colour of the object of which it is a boundary.

Figure 11.

Or consider *a rectangle sharply divided into two colours*, grey and black.

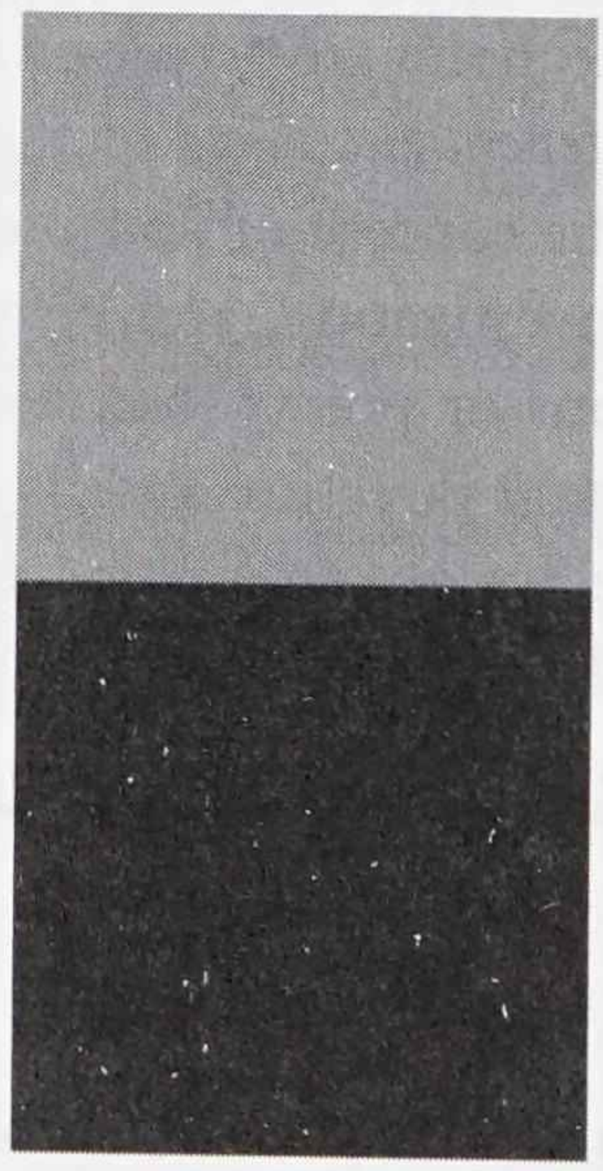

Figure 12.

From this point of view, a grey line and a black line *coincide*.

An example of the *complexity of the role* played by boundaries in actual perceptive wholes is the following:

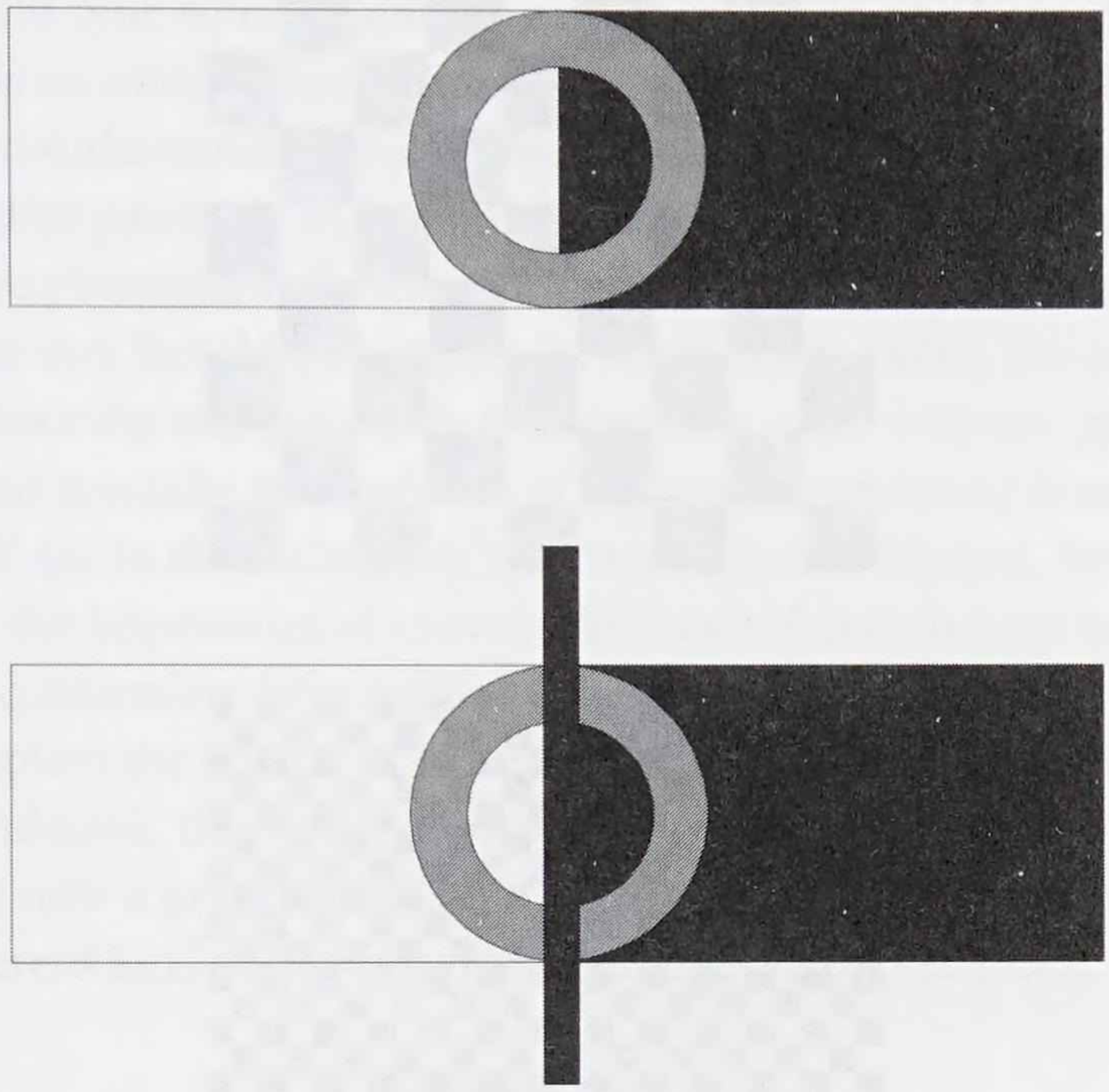

Figure 13.

Take a grey ring which lies on a rectangle, half on a black surface and half on a white surface. The colour of the ring is relatively uniform, even if, according to the simultaneous brightness contrast, the half of the ring on the black surface should appear lighter than the other half on the white surface.

If, however, we separate the two halves by a black thread stretched vertically on the boundary between the two surfaces, simultaneous contrast is immediately re-established.

The fact is that the ring's surface, *taken as a whole*, is unitary and seen as uniform. If we split it into two parts, into *two sub-wholes*, the two parts acquire a relative independence and the colour changes (for the distinction between non-independent and independent parts of the percept cf. again Husserl, 1900/1901, Third Logical Investigation).

Boundaries and coincidence of boundaries may in principle be *indefinite*, as demonstrated by the phenomena of *perceptive fusion* (*Verschmelzung*) of the different aspects (see above, §2).

In fact, imagine a red and a blue chessboard.

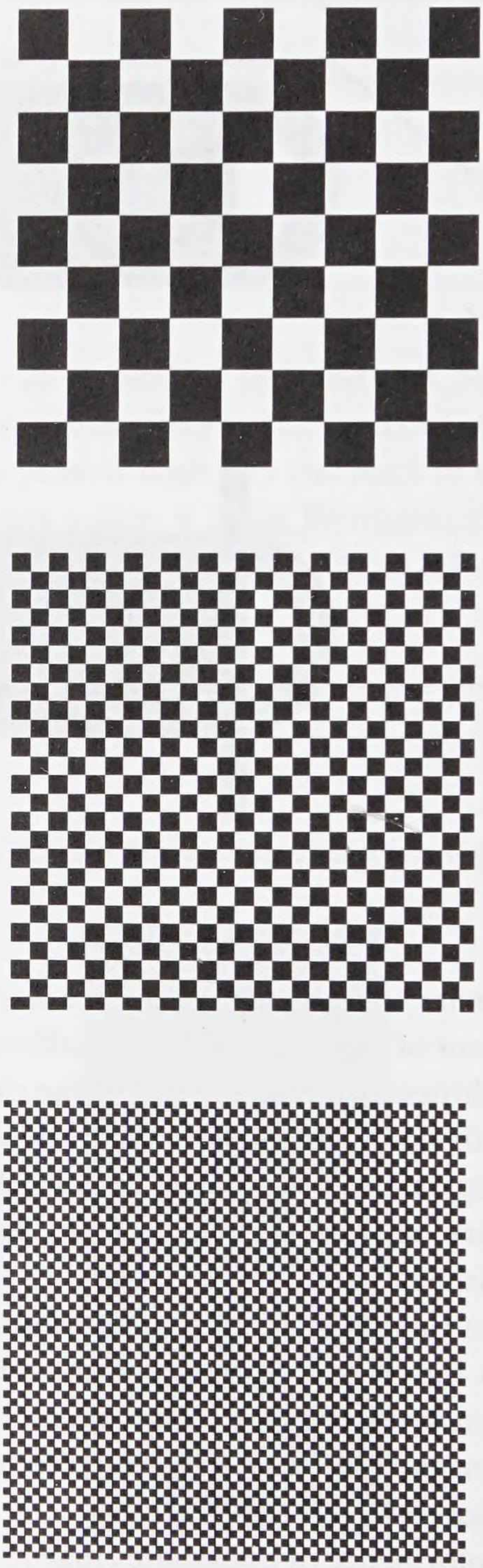

Figure 14.

By progressively reducing the *spatial extension* of the red and blue squares, one obtains the perception of *violet* (examples of this type are provided also by Ruskin: see Ruskin, 1857). Between the two stages, i.e., when one distinctly sees red squares and blue squares, until the moment when one has a perception of violet, there is an intermediate moment in which the chess-board is perceived as *something simultaneously red and blue* (think again of a Seurat painting) even if *not* in the *same positions*. This rendering is due mainly to two facts: the first is an assimilative phenomenon, when the coloured areas are small but still distinguishable (see von Bezold's examples in von Bezold, 1876); the second is due to the blue, since the margin which it forms with other colours (generally with all colours, but specially with colours of the same brightness) is not stable, but tends to 'shift' (as in the Helmholtz's 'fluttering heart' illusion. See Helmholtz, 1867): hence the impression of movement (I owe this comment to Da Pos).

What is continuous here assumes the character of 'reddish' and 'bluish,' and again displays the feature of a coincidence of boundaries. (Brentano, 1976. See also Koenderink, this volume, on ambliopia).

Consider now a grey disc which can be *divided into parts*, and in different ways, by different kinds of lines (which may also be curved lines):

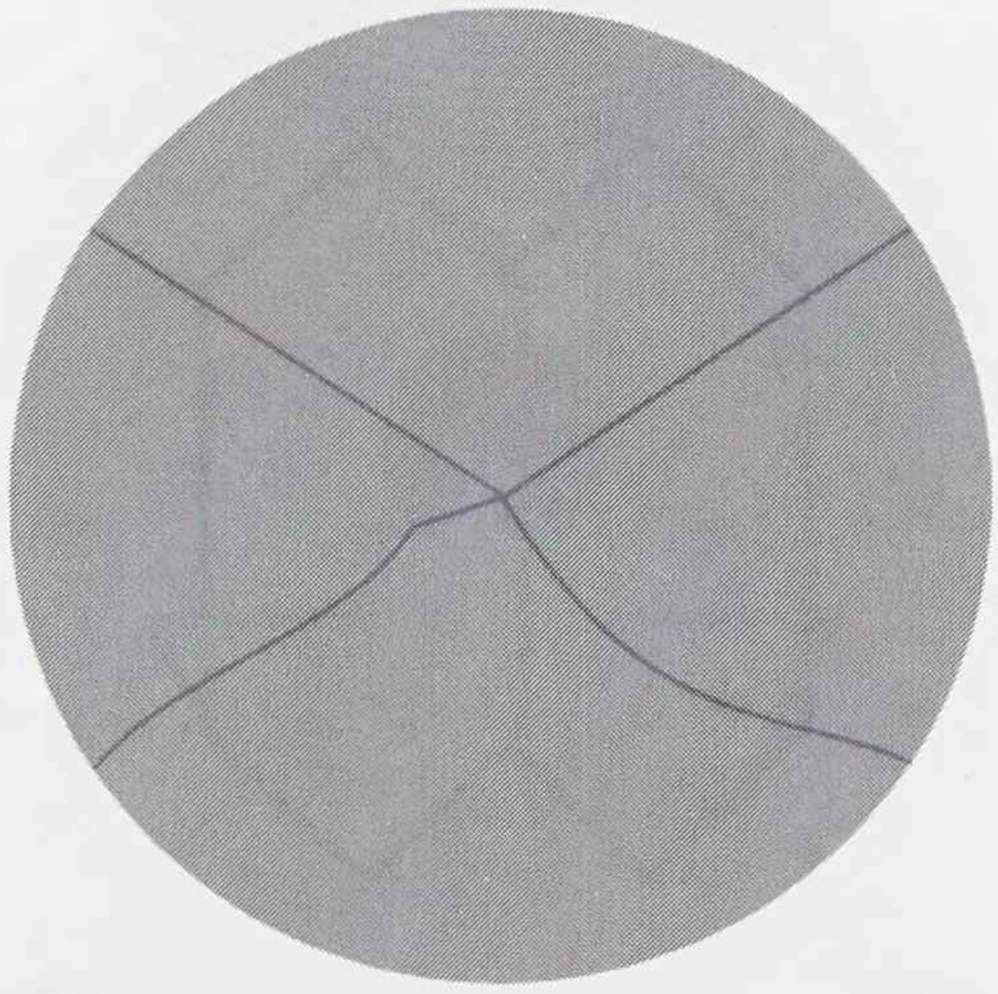

Figure 15.

In this case there is *coincidence of boundaries*, which means that the *boundaries of the sectors* of the disc *belong to every part* of the disc.

Another example of the coincidence of boundaries is provided by the *boundary of two crystals* joined on one side.

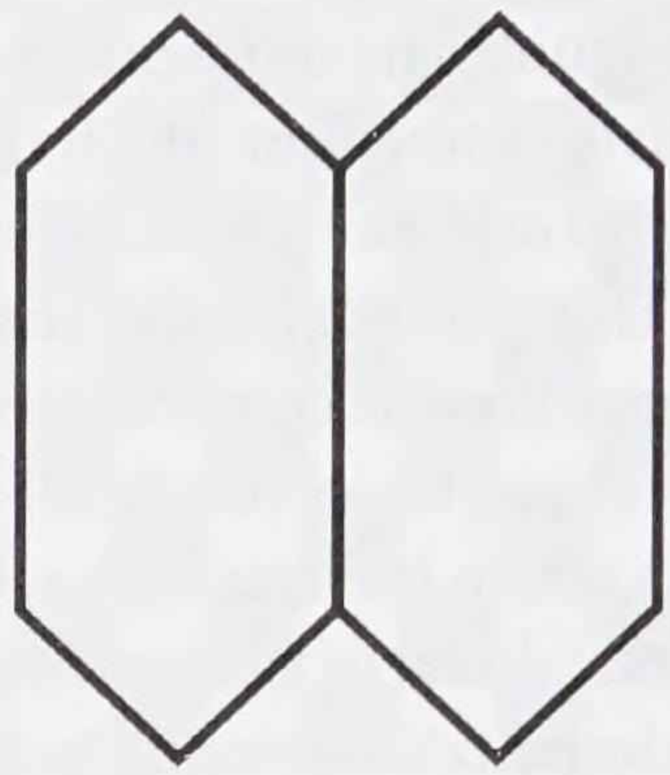

Figure 16.

The boundary belong to *both* crystals (in this case, the unilateral function of boundaries in 'regular' Rubin figures does not hold. See Rubin, 1949; and below, §7). But note that, if the boundary is displaced in a certain direction, making them overlapping by only few millimetres, the masking phenomenon arises.

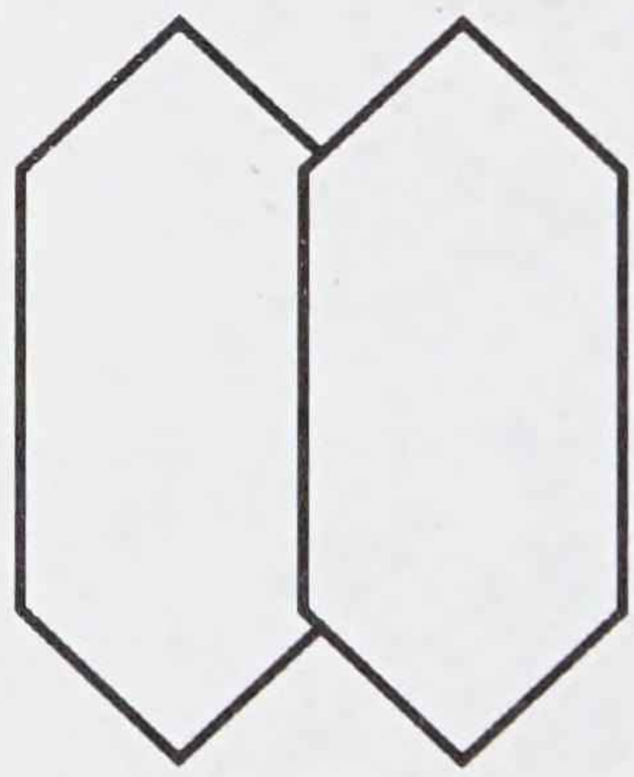

Figure 17.

The role of perceptive *boundaries* is particularly evident in stereokinetic phenomena, where the borders are seen clearly while the mass is blurred, or in cases of amodal perception (Musatti, 1924; Kanizsa, 1991; on the concept of amodal see Albertazzi, unpublished. On the complexity of the related dynamics of perceptual continua see below, §7).

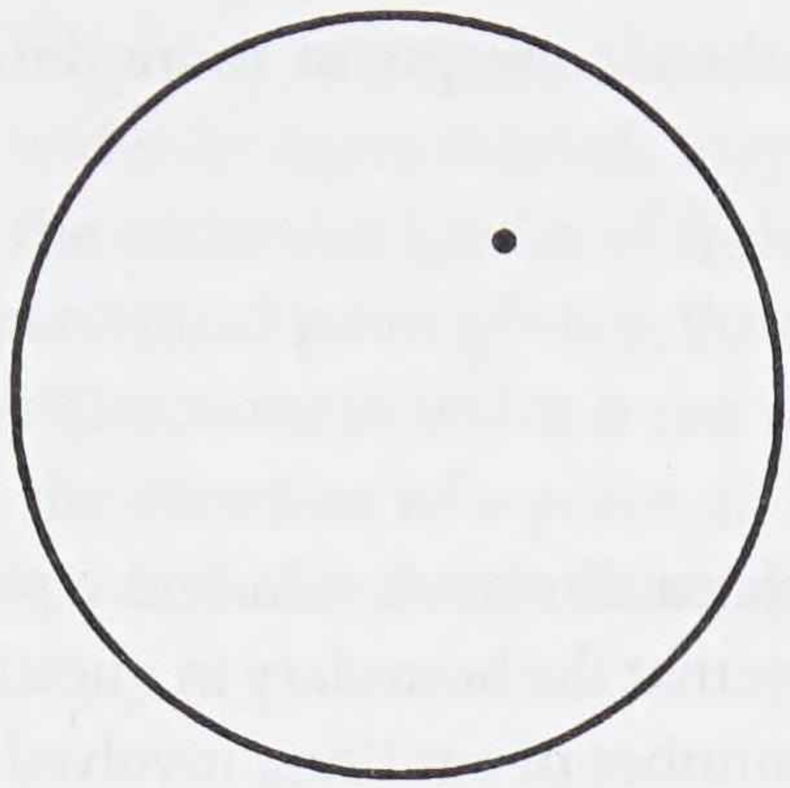

Figure 18.

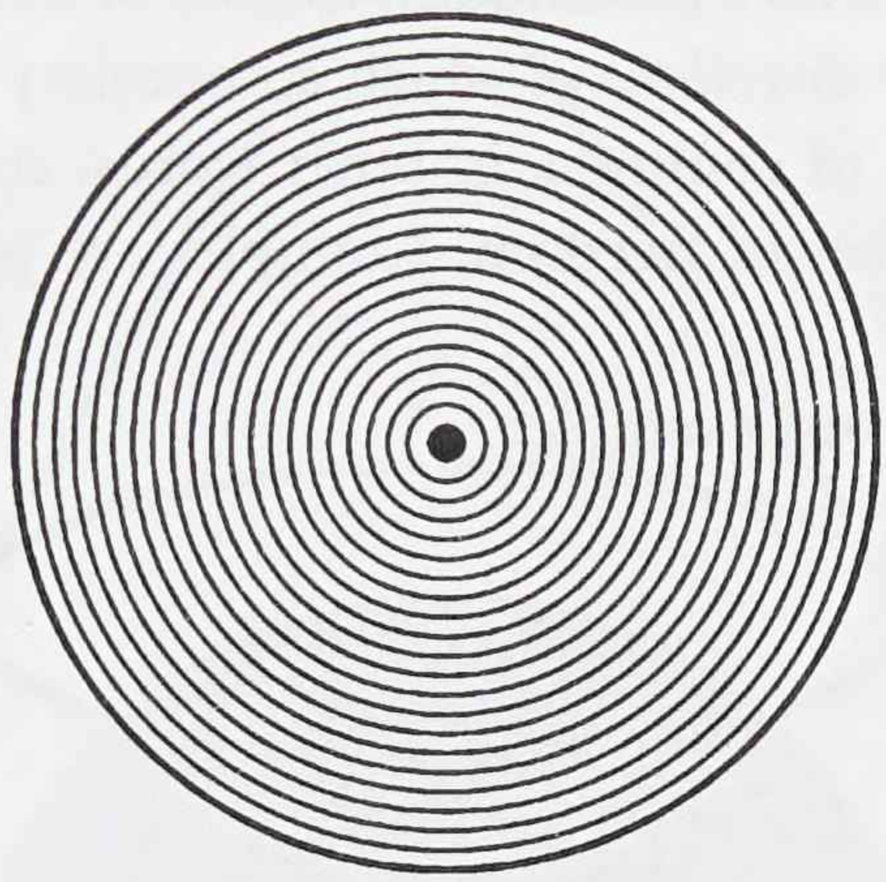

Figure 19.

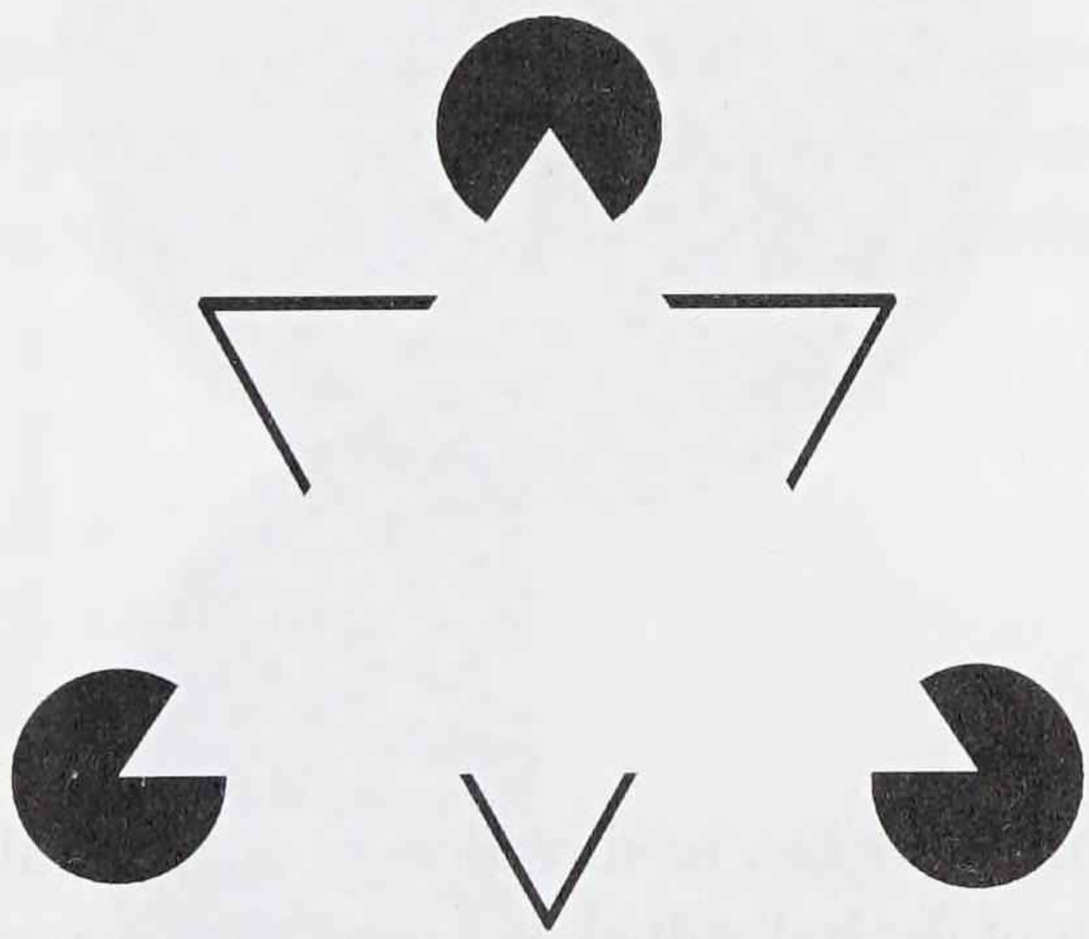

Figure 20.

From this preliminary and elementary empirical-experimental exemplification of the characteristics of perceptual continua, we may derive its base concepts of *direction* and *velocity*.

I shall now analyse these concepts in more detail again on the basis of examples.

5. Direction

Perceptual continua display a direction, which is a *property of boundaries* and depends on the *continuum* that the boundary in question delimits (or, at higher level of complexity, the number of continua involved in the percept(s) and/or in the field(s)). There may be *fullness of direction*, or *otherwise*, in which a *boundary* is connected with a continuum. *Greater* or *lesser direction* means that there are *more or fewer directions* in which a boundary is connected to a continuum. The direction of continua, in other words, coincide with its 'liberty of movement' or degrees of freedom. Examples are provided by Paul Klee's paintings.

Consider the following example:

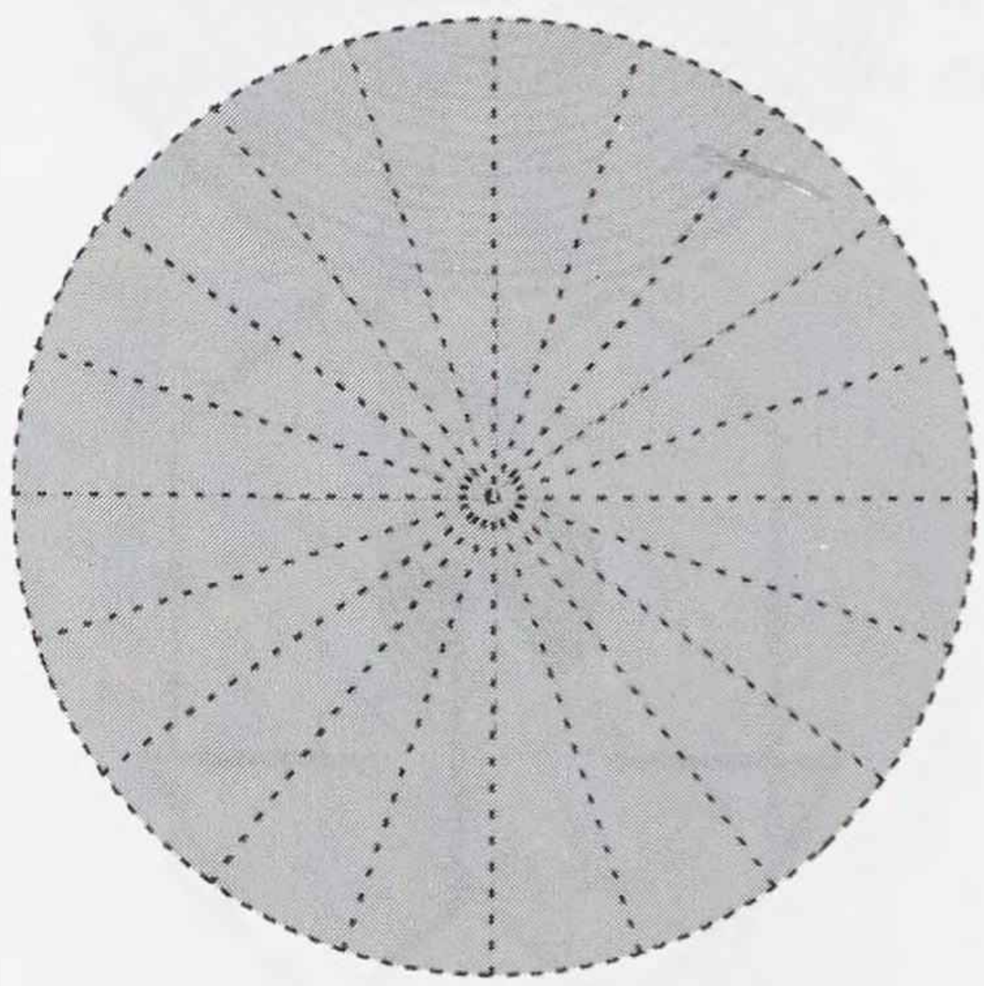

Figure 21.

The figure shows that there can be direction of the central *point* internally to the sphere, direction of the individual points on the circumference, and so on; and then direction of the *radii*, of the *diameter*, of the *circumference*, with the difference that the direction of the central point is *total* (in the sense that the point can move in all directions); while the direction of the individual radii, or of the diameter, is *limited*. Moreover, every point *on* the circumference is wholly limited as to its freedom of movement.

Direction, like any multiplicity variation, *admits of a more and of a less*, in the sense that it may be wider or more limited, may have greater or smaller numbers of direction, in the sense that grades of freedom increase (see Introduction). Hence, from a perceptual point of view, the direction of a *point of the interior* of a *cone* – i.e., the directions in which it can move – is wider than that of a point on its surface; the direction of a point on its surface is wider than that of a point on its vertex. And also the direction of the vertex is wider, the less the cone is pointed.

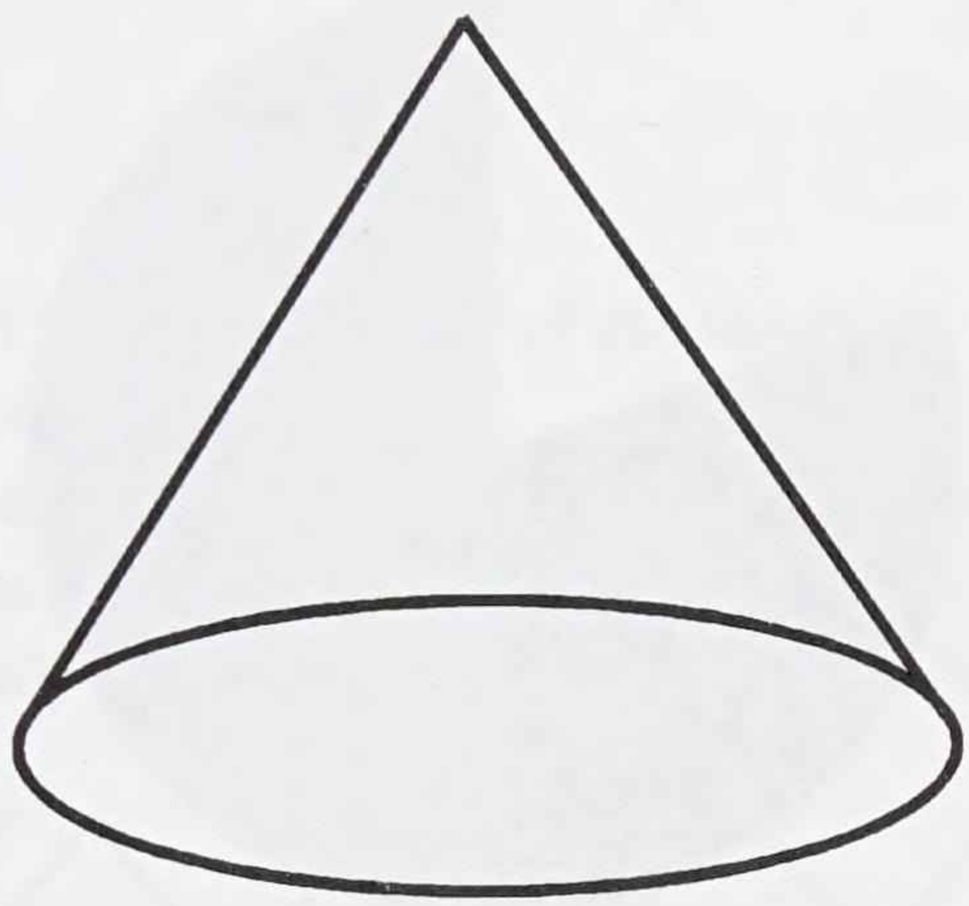

Figure 22.

Other examples of the *direction* of continua are provided by coloured discs. For example, take a *non rotating* coloured disc divided into four quadrants: green, blue, red, yellow (the figure in the text has been printed achromatically).

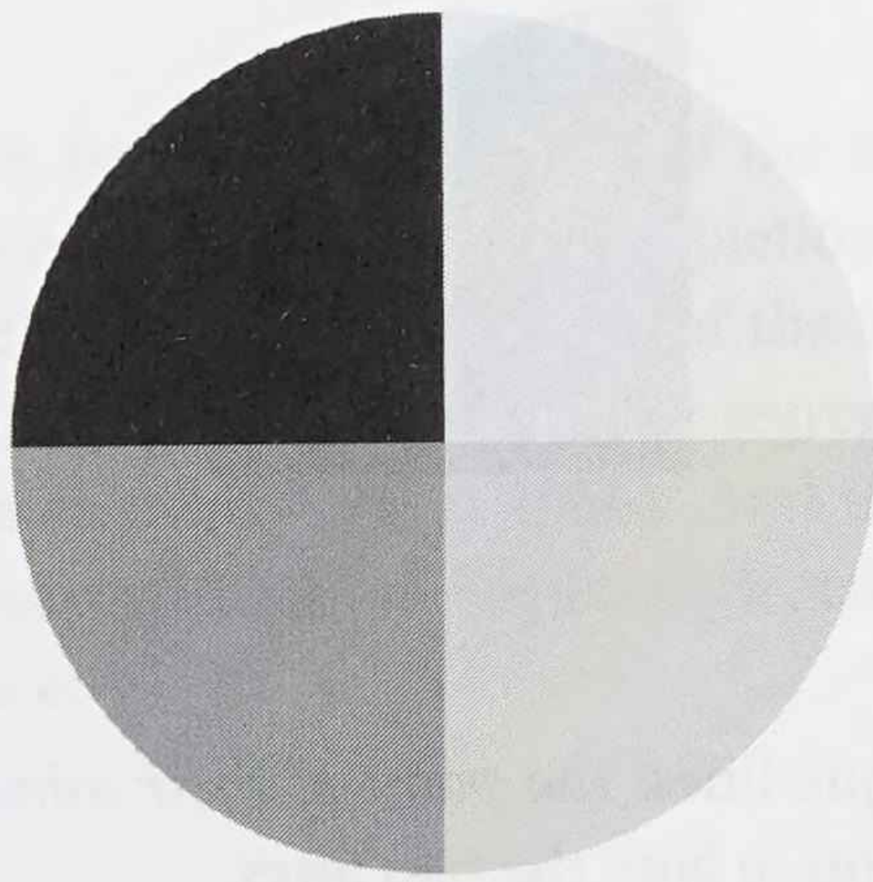

Figure 23.

This problem was posed by Brentano in his theory of continua. He started with the questions of whether or not the 'medium point' is *detachable*, and of its colour, if any. According to Brentano, the medium point is divided, as he puts it, in a *fourness* of points, by which he means that the point is simultaneously green, blue, red and yellow (Brentano, 1976: 16). Which also means that the medium point is *not detachable*, because there is coincidence of more points.

Consider also the *midpoint of a disc* and suppose that some of the *quadrants* of the disc are *removed* (ibidem).

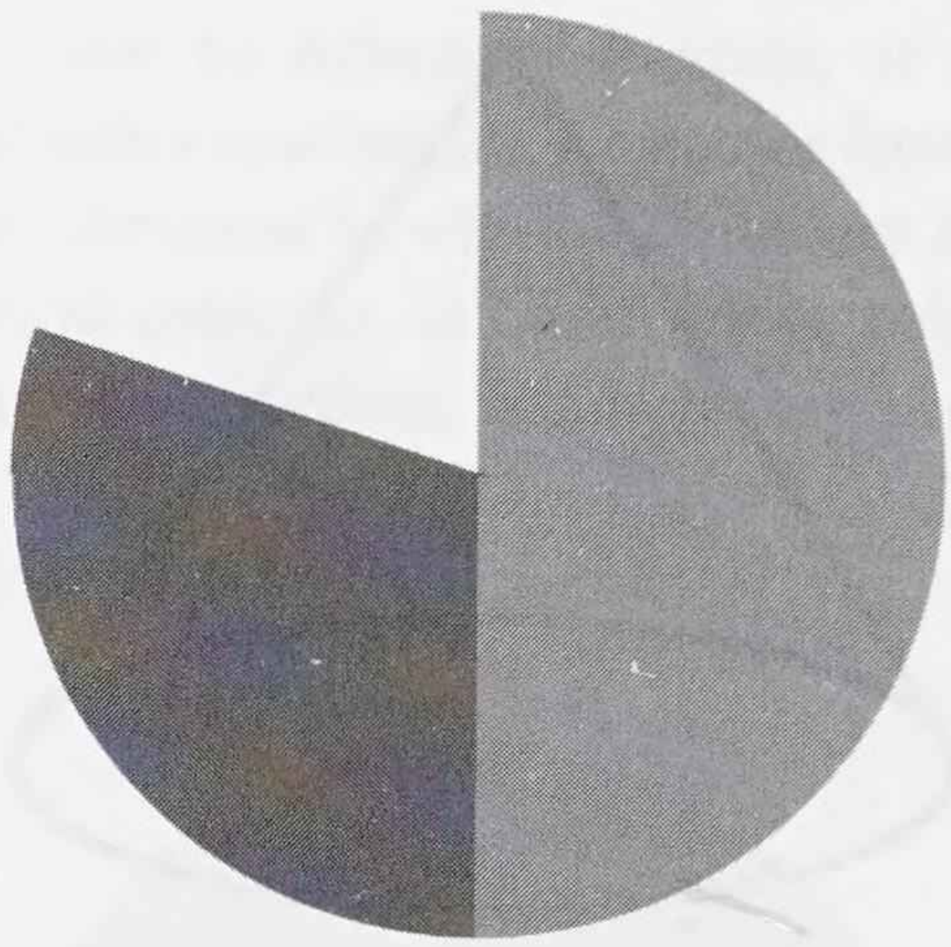

Figure 24.

As each quadrant is removed, the *direction diminishes* and the *point becomes a boundary in fewer dimensions*. Here the medium point has *1/4 direction* of the dark grey point of the dark grey quadrant.

Figure 25.

Take two crossing oblique lines: the *point of their coincidence phenomenically splits into two* and *pertains to both* the two lines.

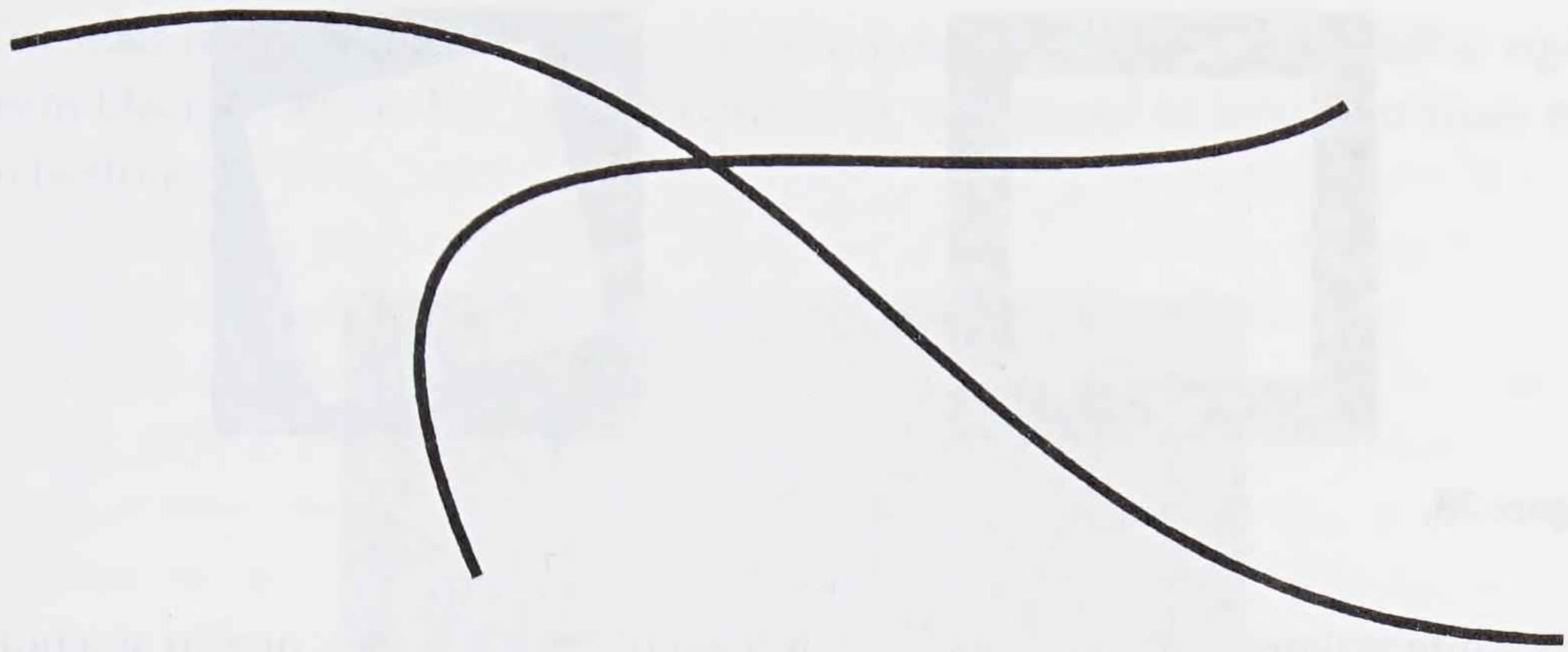

Figure 26.

This obviously recalls the development of the theory in the Wertheimer laws, in this case of *good continuity*.

More generally, direction influences the *degree of grouping* in perceptual units: in fact, elements that differ by 180° are not strongly grouped; by contrast, those that differ by only 45° produce strong grouping (Palmer, 1999: 259):

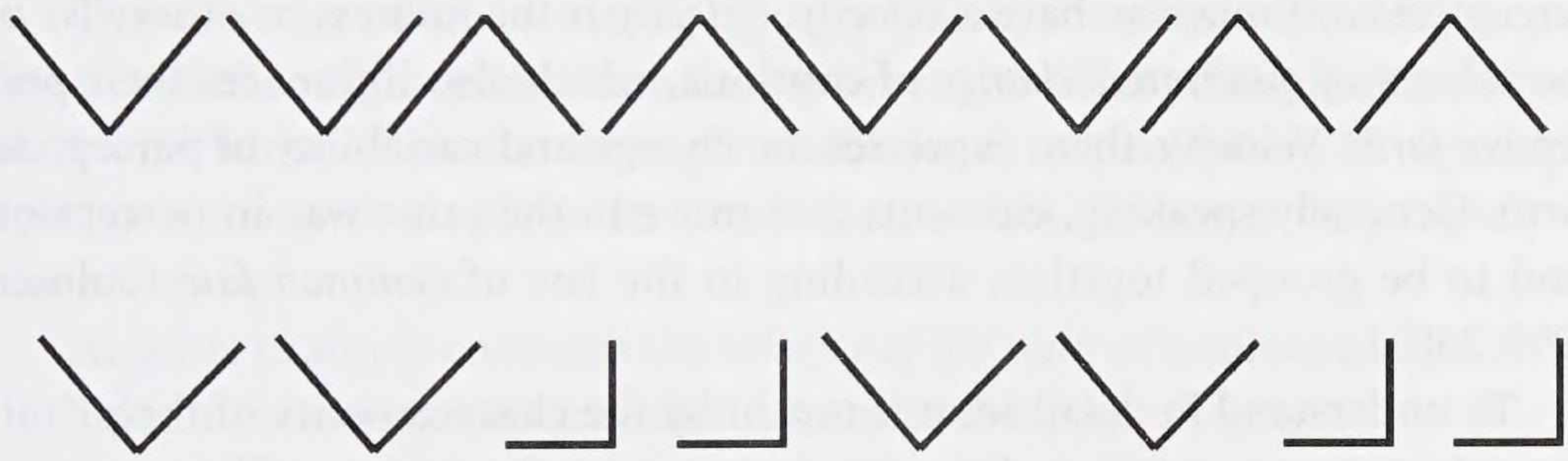

Figure 27.

A much more complex, but evident example of the role of direction in perception is given by phenomena of amodal completion (as Helmholtz himself observed), where the direction of the contour of the occluded figure changes (Helmholtz, 1867); or by phenomena of texture segregation based on the orientation of the texture elements (Beck, 1966). And the same holds for phenomena of *figure/ground* organisation. For example, take a black oblique white square on a black surface:

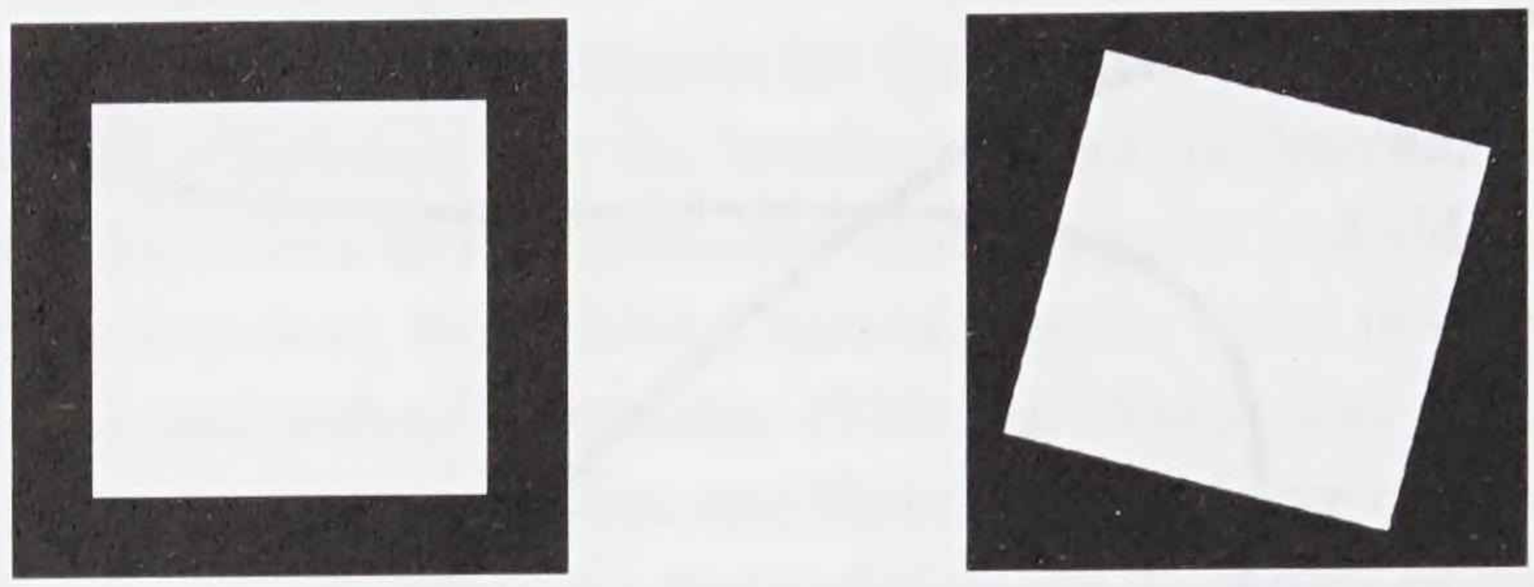

Figure 28.

The white square appears as an object in front of the black one, or also as a hole in the black object (Bozzi, 1975).

The direction of continua also plays a major role in *edge discontinuity*. This consists in a sudden change in the direction of a contour, as apparent in the corners of a square (Palmer, 1999: 290).

6. Velocity

Perceptive continua also have a *velocity*. *Velocity* is the fullness or otherwise of the *velocity of qualitative change* of continua, which also influences their perceptive *form*. Velocity, then, expresses the change and variability of perceptual form. Generally speaking, elements that move in the same way in perception tend to be grouped together, according to the law of *common fate* (Palmer, 1999: 258).

To understand in detail what is meant by the characteristics of the primitive, take two concentric circles around a common fixed centre. The curvature of the inner circle has less intermediate spatial loci to pass through than does the curvature of the outer, i.e., it has *more velocity*.

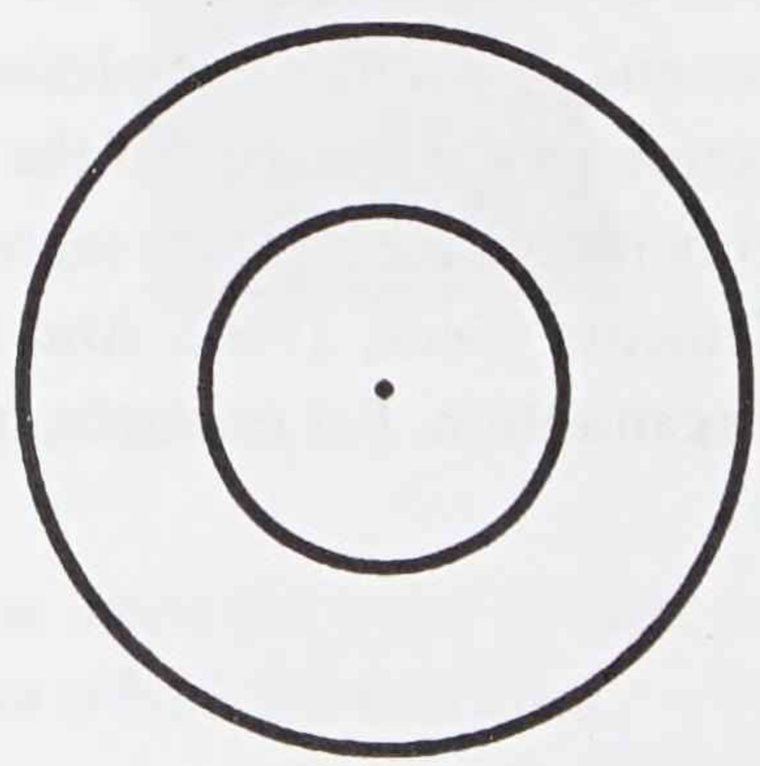

Figure 29.

Consider next the case of a *rectangle which changes in colour from left to right*, from black to white, but instead remaining unchanged in its colour from top to bottom.

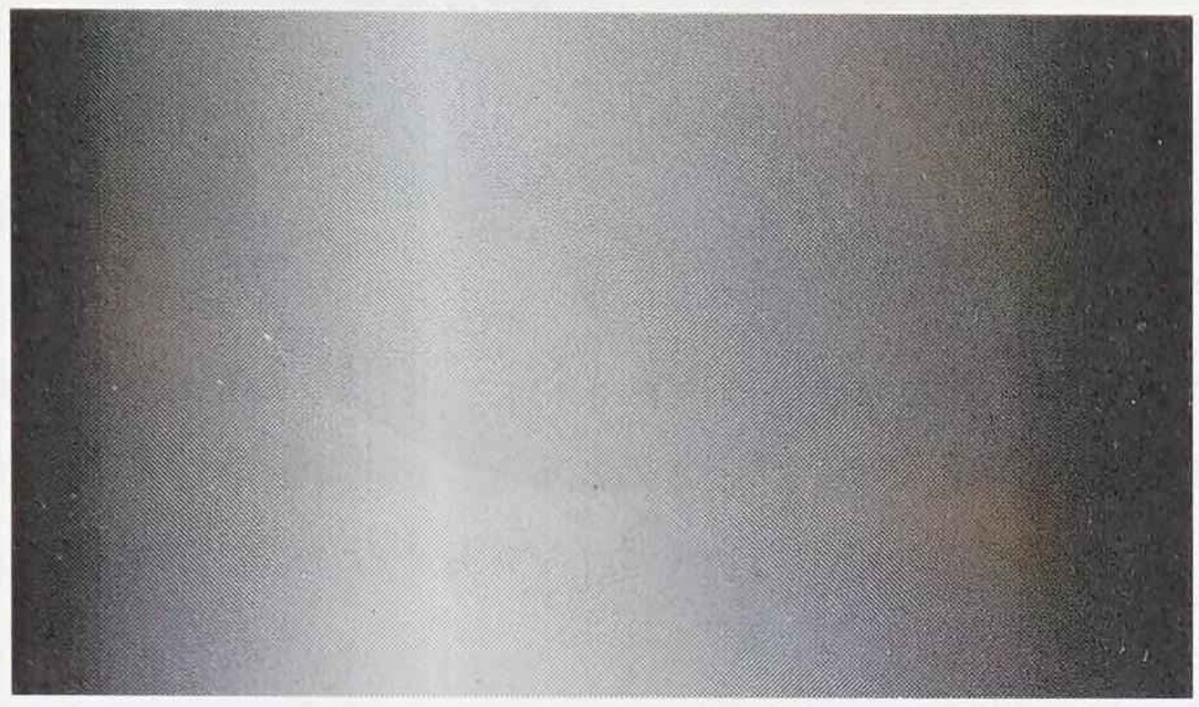

Figure 30.

In this case, *from left to right* the rectangle has *lesser* velocity at every point, like the *boundary in other directions*. Vice versa, the rectangle has full velocity from top to bottom (this is what Brentano called "variation of plerosis").

This is a case of an *increasing* velocity which, if we draw an oblique grey line from left to right, phenomenically gives rise to a line which is alternatively black and white. A similar example is obtained, in perception, if we simply *light up a transparent sphere*. Its luminance, in fact, decreases very rapidly as one moves downwards.

Another example concerns the *velocity of the radii* of a coloured disc.

Take an homogeneous grey disc. Its radius *R* is *perfectly grey*.

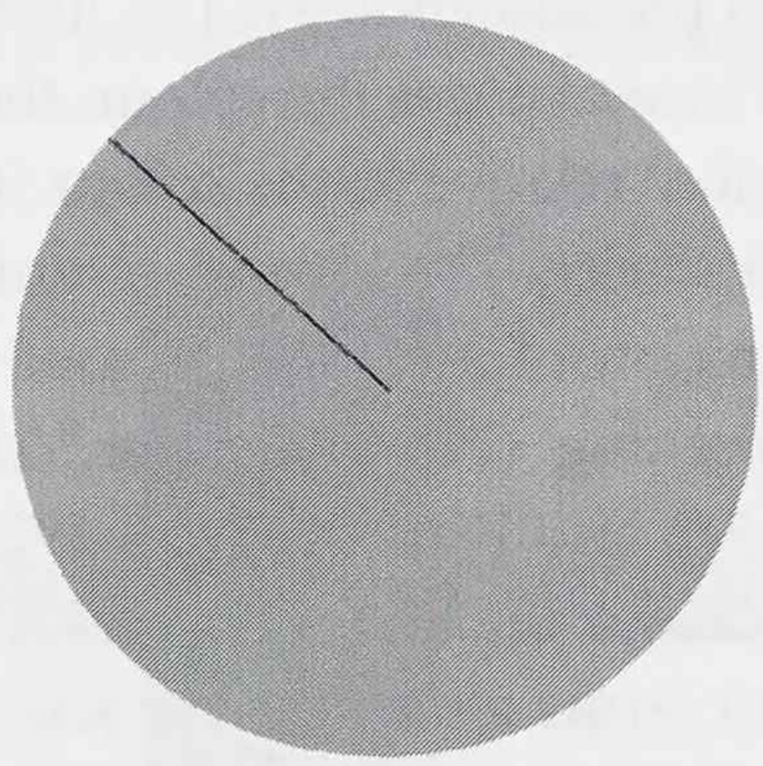

Figure 31.

Then take another disc, divided into two parts, grey and black.

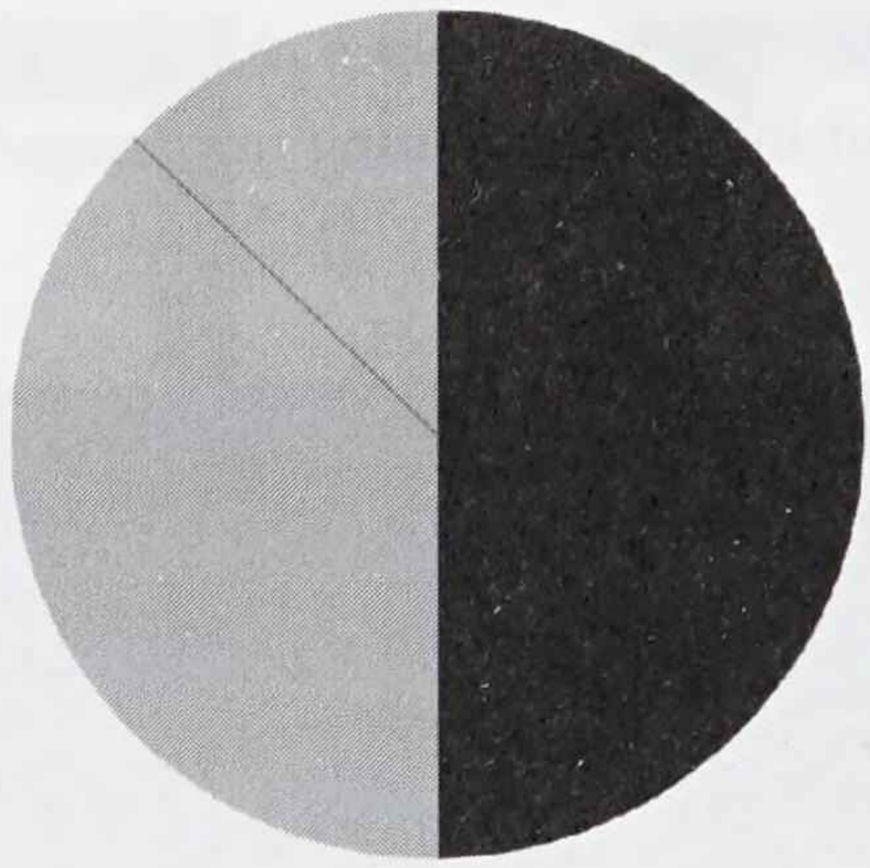

Figure 32.

In this case the *grey radius forming the boundary* between the grey and the black semispheres is not as perfectly grey as the radius in the grey semisphere, because it is a boundary *beginning in variation toward black* (Brentano, 1976. On scale space operations see Koenderink, 1993).

Brentano's originary conception is easily understood if it is related to Hering's theory of *unic* or elementary colours (*Urfarben*). Hering's system distinguishes six fundamental colours (red, green, blue and yellow, plus white and black) situated on four scales of opposition in a bipolar arrangement. The colour parameters are chromaticity, whiteness and blackness. The nuance is the *locus* of all possible colours, which are perceptively given with a certain degree of resemblance to the prototypical colour in question, whether it is white, red, green, and so on (for the concept of 'locus' see the Introduction).

The point emphasised by Brentano also bears out the correctness of two assumptions of Husserlian phenomenology. The first is that, in the perceptive recognition of the appearance of a specific colour, the recognition is made on the basis of 'eidetic variation' relative to the colour itself, of which the colour perceived is a typical singularity. The second assumption, closely connected to the first, is that recognition of a colour is based on reference to implicit 'semantic categories of meaning' (like 'whiteness,' 'redness,' 'yellowness,' and so on) (Husserl, 1900/1. See also Benussi, 1923–1925; Albertazzi, 1998a. For a scientific treatment of colour see Sivik, 1997: 177. For confirmation of the semantic account of colour terms see Berlin and Kay, 1969).

Then, as another example of perceptual velocity, take the *segment* separating the two differently coloured parts of the disc: *velocity at the point in the middle is greater* than it is at a point on the circumference because the *variation from grey to black is slower on the circumference* than it is at the middle point of

the disc. Then the first radius, as the *boundary of what is variable, undergoes a difference of variation* (Brentano, 1976).

All these phenomena, descriptively elaborated by philosophers of the phenomenological persuasion, are also visible in perception, for example in *Maxwell's rotating discs*. Given a disc divided into two parts, red and blue, in fact, at *low* speed variation, one sees in this case a blue figure moving on a red disc.

These phenomena have also been analysed by Metelli and by Witte in their experiments on *apparent movements* (Metelli, 1940, 1975; Witte, 1960): phenomena which, as Shepard observed, fall somewhere between perception and imagery (Shepard, 1984: 423. See also Shepard and Judd, 1976).

Another example of the velocity of perceptual continua is the following (Petter, 1956):

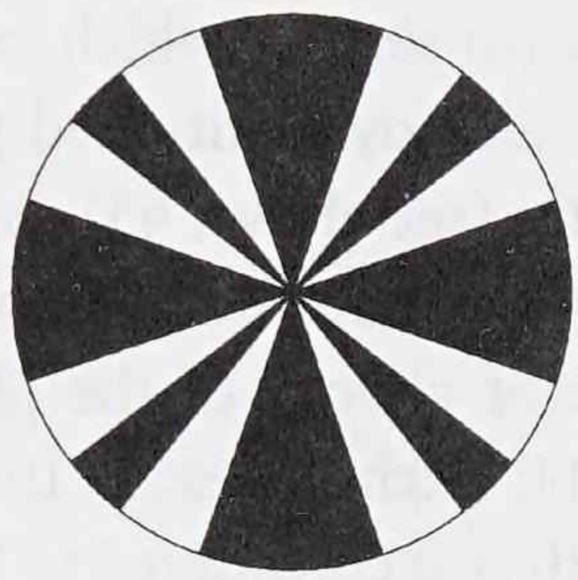

Figure 33.

In this case the cross with *wider arms* is *at rest*; instead, the cross with the *narrow arms rotates at uniform velocity* behind the first one. From a phenomenal point of view what one sees is a *jerky movement alternating with pauses of rest*.

Finally, an example of *chromatically homogeneous surfaces* whose *contours move at different velocities* is provided by the following experiment (Vicario and Kiritani, 1999: 97–98).

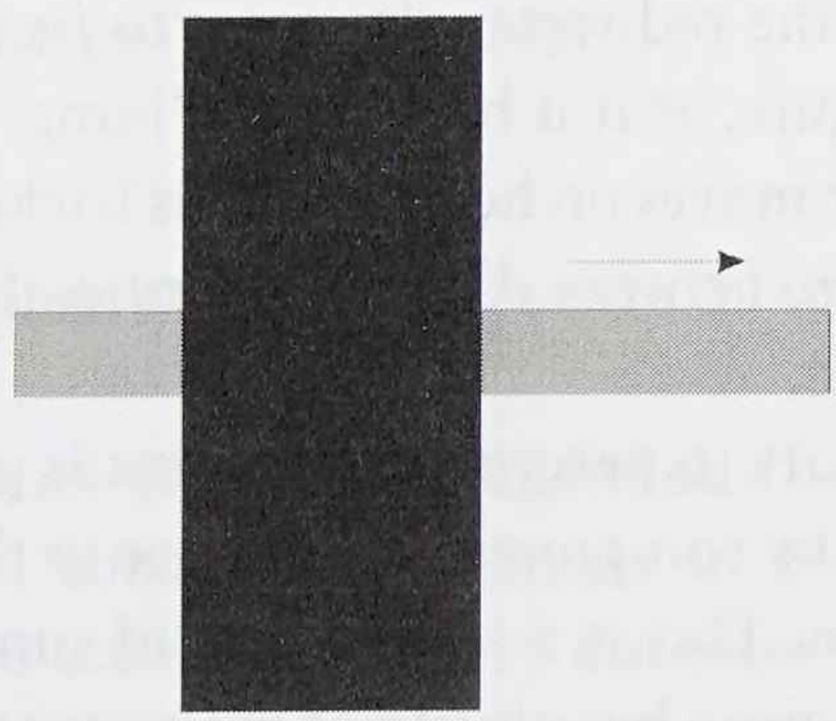

Figure 34.

A vertical black rectangle (1.5 × 4.5) is displayed against a white background on a computer monitor. There is also a light-grey horizontal rectangle (1.7 cm in height and of varying length, about 10 cm) which moves from left to right at a low velocity (1 cm/sec).

The experiment shows that the *perception of a rectangle in movement* is also connected with the width of the vertical screen. If the screen is too wide, in fact, instead of a single rectangle in motion, two small and independent rectangles are seen in movement: the one enters from the left side of the screen, the other exits to the right. If, instead, the screen remains the same but the velocities of the two surfaces in motion are changed, the unitariness of the rectangle is connected to this difference in velocity. In fact, if the ratio between the velocities is less than 1:2.5 (or 2.5:1), a single unit continues to be seen; if the ratio is greater than 1:3 (or 3:1), two rectangles start to be seen, one slower (or faster) that enters and another faster (or slower) which exits (idem).

Of the same type are the already mentioned phenomena of perception of causality analysed by Michotte (see above, §3). Also the 'jump' effect and the 'unhooking' effect, in fact, are due to the dynamic relation between *orientation* of *direction* and change of *velocity* of the phenomena appearing in the perceptive fields (Heider, 1944; Michotte et al., 1962. See above, §3).

In particular, the *jump* effect is considered to be an example of intentional (inner) movement and depends on *velocity relations*, rather than on figural contiguity or on contact by the object with some elements of the background (Michotte, 1954; Gyulai, 1987).

The jump effect, in particular, is obtained when, for example, a red rectangle moves at constant velocity horizontally from left to right on a background with a black stationary rectangle in the middle.

When its right side touches the left side of the black rectangle, the red rectangle suddenly changes its velocity to a higher constant value, and then resumes its initial velocity when its left side coincides with the right side of the black rectangle. Briefly, the red rectangle seems to *increase its velocity* while it passes over the black figure, as if it has made a 'jump.' Since this effect is also obtained when an object moves on homogeneous background, the implication is that it is due to *relations between different velocities* than to figural contact or contiguity (Gyulai, 1996).

An example of velocity in perceptual continua is given also by the Gestalt law of *common fate*, i.e., by components that move in the same way to give rise to a group configuration. This is a special case of similarity grouping, where the essential property is given by velocity of movement.

A final example of velocity of perceptual continua is provided by stereokinetic objects displaying a very well definite height.

For example, when measuring the apparent height of a 'cone' appearing on the basis of a two-dimensional figure (circle + point as in Fig. 18) in motion, Musatti minimised *relative distances*, because constant relative distances between the various points of an object define a *rigid* object, both 'real' and 'perceptive' (Musatti, 1924).

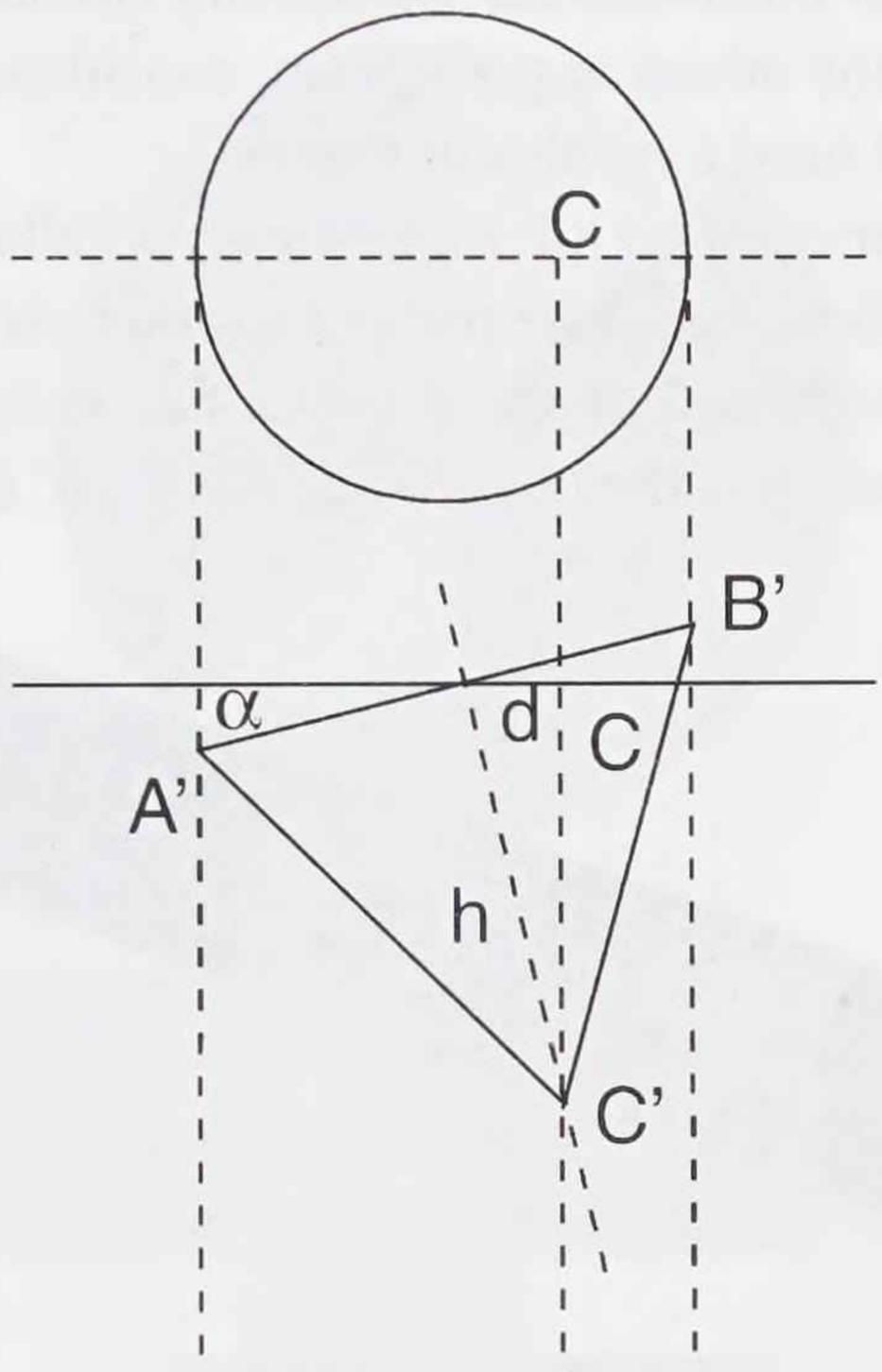

Figure 35.

Vice versa, Zanforlin, following the *minimum principle assumption*, supposes that our visual system minimises *relative velocity differences* among all the various points of the pattern (Zanforlin, 1988).

7. Dynamics of complexity

The elementary properties of perceptual continua (extendedness, boundary, direction, velocity, etc.) considerably increase in complexity in actual perception. This is because activated in every duration are multiple and multiform interconnected continua: for example, time, space, colour, sound, touch, warmth, etc., and in multiple variations.

Consequently, the characteristics that prevail at the level of elementary descriptive properties present themselves differently at a higher level of complexity. The true problem in the dynamic construction of a theory of perceptive continua, therefore, is accounting for the complexity of the ongoing relations, starting from its 'elementary characteristics' (in the Kantian sense: on this concept see Albertazzi, 1998a). Some examples follow.

Let us first consider Brentano's example of the bluish and reddish chessboard. This case, which illustrates the elementary characteristic of *coincidence* of boundaries, like many others in perception, considered at a diverse perceptive complexity, would need a surplus of theory.

Consider the phenomenon of *transparency* (Vallortigara and Bressan, 1994). If instead of a chess-board we present another visual object, like a cross in *transparency*, the phenomenon of perceptual fusion does not take place.

On the contrary, one sees the *two objects*, one 'over' the other.

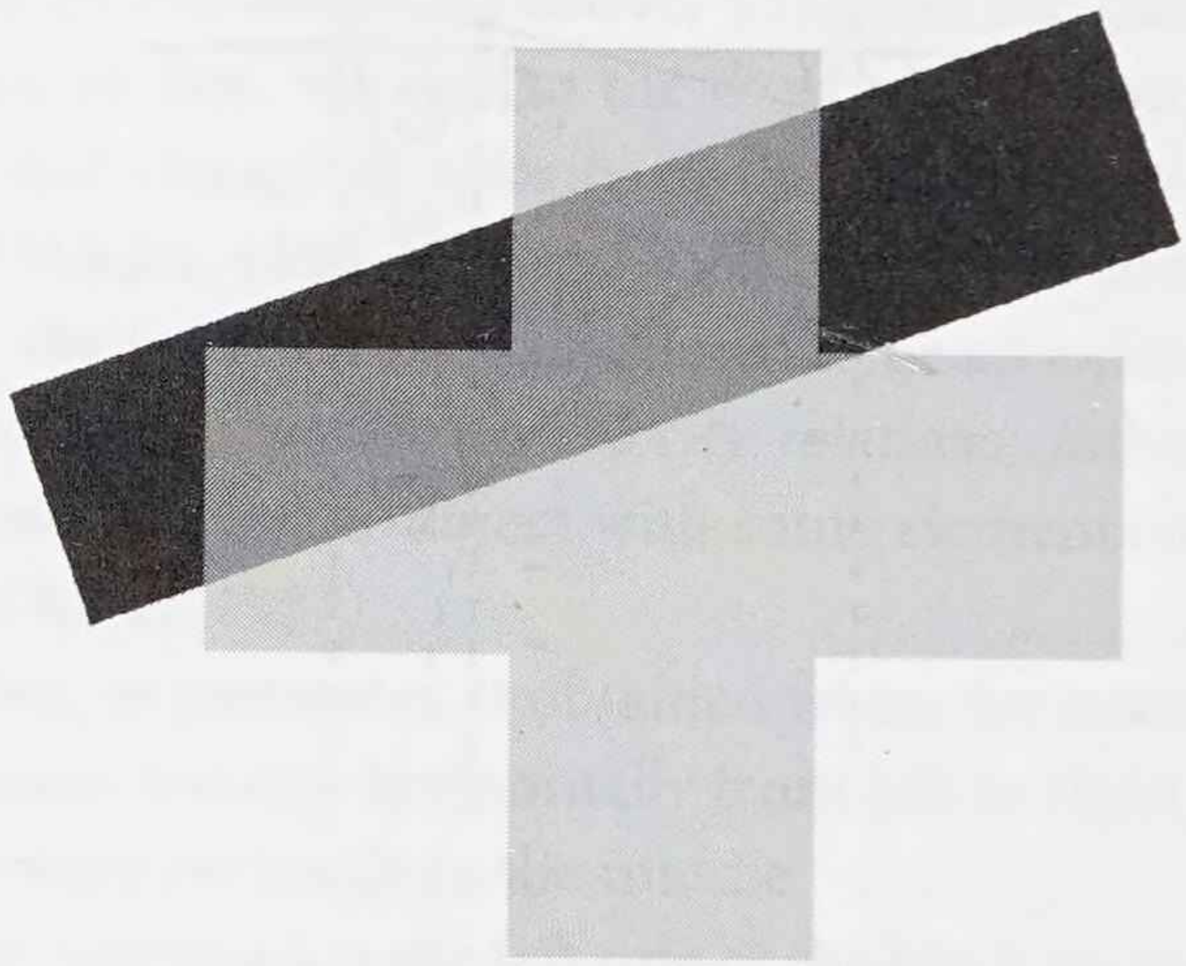

Figure 36.

There are other cases of perceptual complexity in which coincidence of boundaries does not hold. In Gestalt theory this problem goes by the name of the *unilateral function of boundaries*, according to which the ability to recognise shape is *coupled with figure/ground organisation* in the region to which the boundary is assigned. In other words, when perceptually there is a distinction between figure and ground, the *boundary belongs to the figure* and not to the ground as well. In general, when the boundary has *articulated* contours, the configuration figure/ground prevails. For example, if a disc is divided by only one straight diameter, the two parts appear to join, and on the same plane. Vice versa, if the

division is made by an undulating line, one of the two parts seems to lie in front of the other (Attneave, 1972; Massironi, 1982).

Another example of non-coincidence of boundaries in a disc is provided by Kennedy's *beach ball.*

In this case, it sometimes happens that the *pieces* of the disc *do not overlap*, so that the boundaries appear to belong only to the figure, being only *juxtaposed* like those of a beach ball.

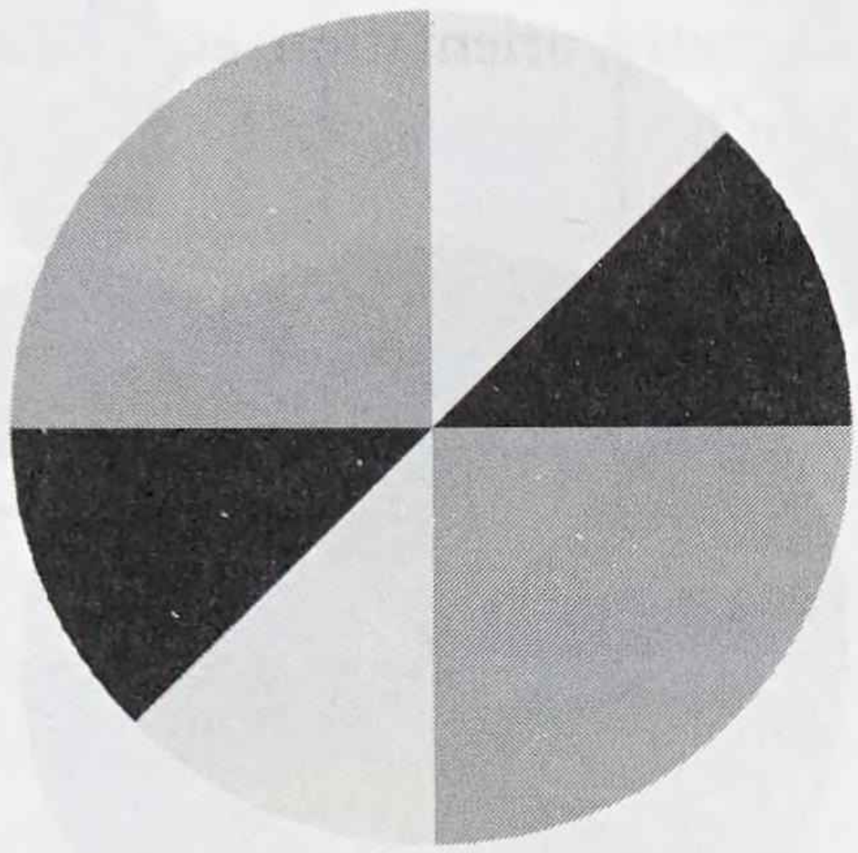

Figure 37.

In the Rubin vase/profile figure, for example, the white region lacking a boundary simply appears to continue behind the black region, and vice versa.

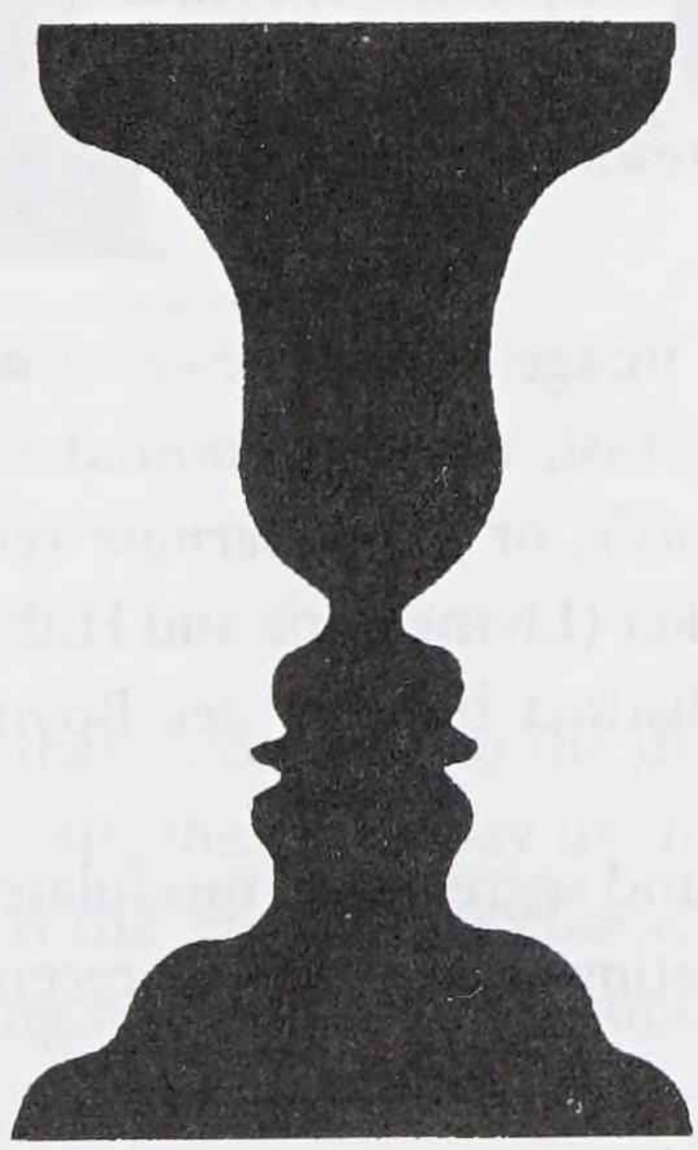

Figure 38.

The Rubin vase/profile figure, however, points up the fact that, if we have a disc divided into sectors, the boundaries among the different sectors *would not* always belong 'indifferently' to any of them.

In fact, when the disc is divided by squared lines, and when some of its quadrants are coloured, it displays the salience of the Koffka *Maltese cross*: in this case, when visible, the *boundary* is *only of the figure*, not of the background, according to the properties of the figure/ground organisation (i.e., figure is mainly thing-like, closer to observer, bounded by contour, its shape defined by contour, convexity, symmetry, orientation, etc.) (Brentano would call this a case of 'plerosis of direction').

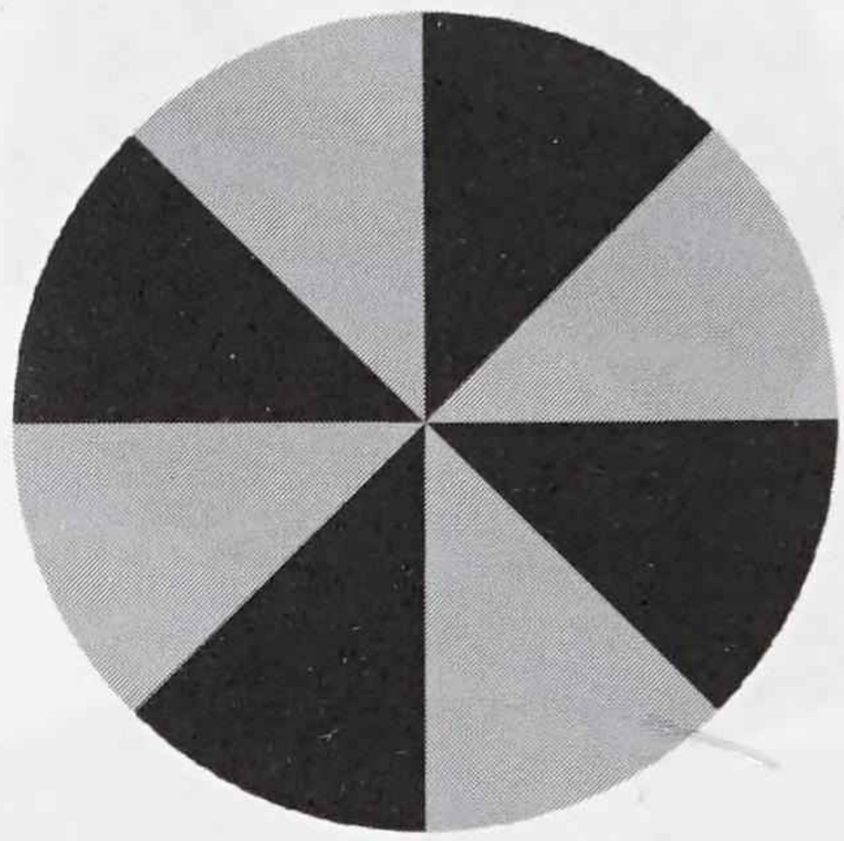

Figure 39.

But in this case we have different *colours, boundaries dividing in different directions*, etc.

At a different level of resolution, Rubin's vase prompts a different rendering, for example:

1. In given conditions of image *luminance–contrast*, one sees *either* the vase or the profiles; by contrast, with *equiluminance*, one instead sees shapeless 'blobs' *simultaneously*, or *they alternate very rapidly*, so that the figure/ground grows weaker (Livingstone and Hubel, 1988. On what has been called as 'minimally distinct borders' see Boynton, in Kaiser and Boynton, 1996).
2. Moreover, figure–ground segregation modulates the *perceived direction* of ambiguous moving gratings and plaids, as recently showed (Tommasi and Vallortigara, 1999.)

Another example of *coincident* boundaries is the *function of direction* when the figure is *reversed*.

In fact, if we reverse the vase/profiles figure up-down, so that the *direction* of boundaries changes, the *figurality is broken* (Peterson and Gibson, 1993: 386). Which clearly means that the direction in continua 'matters'!

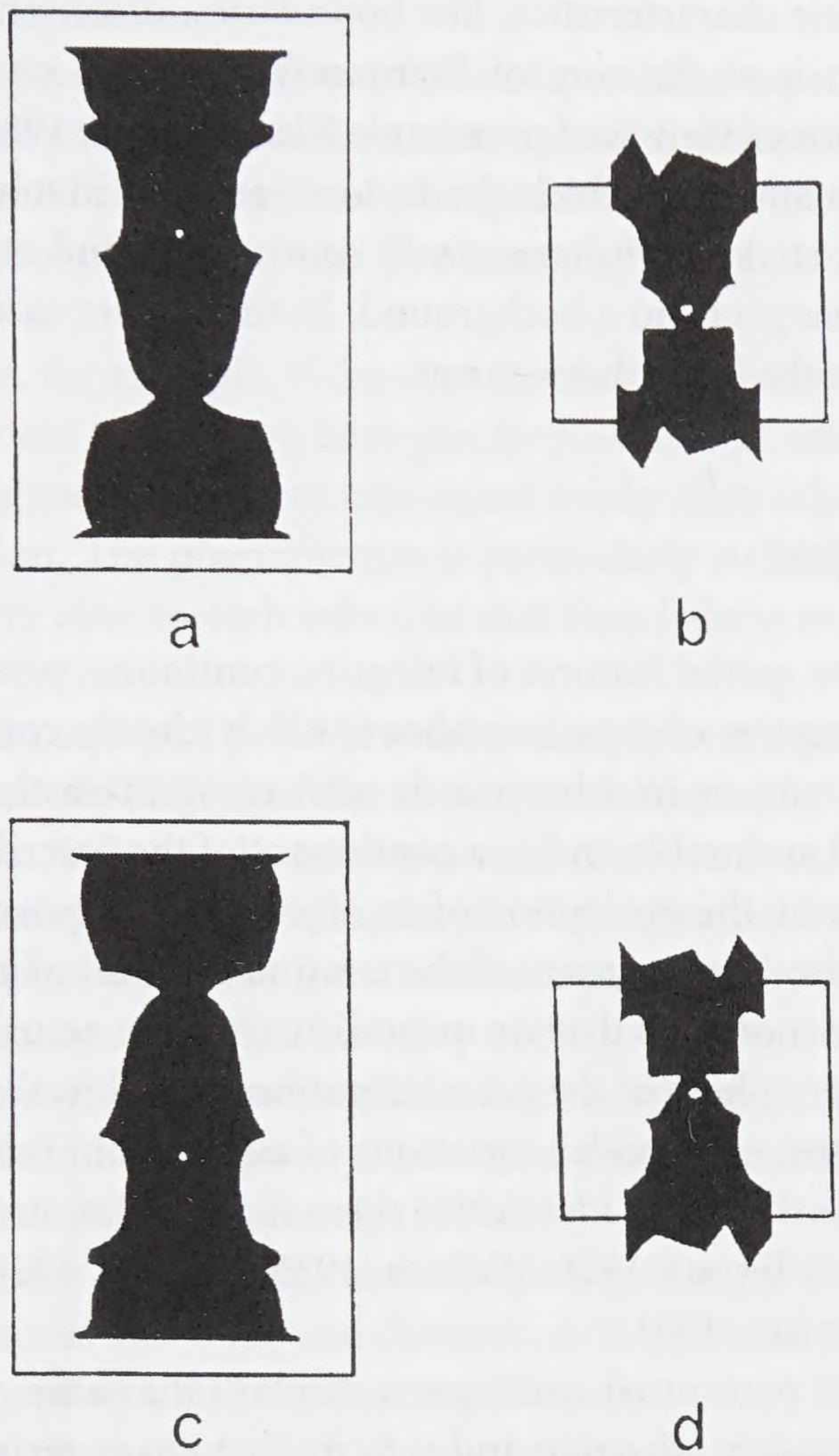

Figure 40.

These last examples show that, according to the different level of complexity of the phenomenic conditions, the *parts* may or may not belong to the *same* phenomenic whole and that the 'elementary characteristics' may *play a different functional role*, according to the given field-conditions. The importance of the role played by parts in the perceptual whole (i.e., by the elementary characteristics of perceptual continua, like boundaries, etc.) has been stressed in a classical study by Metzger (Metzger, 1941).

This is not to imply that Gestalt theory is wrong in its conceptualisation of the above mentioned elements of a perceptual analysis of continua, or vice versa. On the contrary, it means that we have different levels of complexity in perception due to the *multiple and multiform superimposition of types of continua*, and their characteristics, like boundaries, directions, velocities, etc. (This conception is at the core of Brentano's theory of continua. From an experimental point of view see for example Kienker et al., 1986.)

There are situations in which the factors variously involved (form, luminance, attention, etc.) are *phenomenically equi-salient*; and other situations in which *a figure emerges* from a background. In the former case the boundaries are coincident, in the latter they are not.

8. Embodied time

Recognition of the *spatial* features of integrity, continuity, persistency and pre-existence of perceptive objects (see above, §3) is closely connected with the *temporal* continuum, or in other words with recognition that a 'moment of time' is perceived as durable and as a continuant of the preceding.

As we have seen, the perception of an object is made possible by a permanence of perceptive *content-parts* of the continuum, and of perceptive *phases* containing all the moments that we must distinguish in actual perception (see above, §2). In every phase of the actual duration, the 'object' appears content-wise to be the same, even under variations of aspect from one moment to the next, which makes the object *identical* in these slight variations (Husserl, 1966a; Wertheimer, 1923; Ternus, 1926; Wallach, 1935; Musatti, 1926; Metzger, 1963; Metelli, 1975; Kanizsa, 1991).

The temporal perceptual continuum displays the same characteristics of *extendedness*, *boundary*, *direction* and *velocity* that characterise the space continuum. As mentioned, these concepts, too, have been developed from both a theoretical point of view (at least in their initial characterisation), and an experimental one.

In the former case they gave rise to the foundation of a theory of intentionality in Husserlian phenomenology, in the latter to pioneering research by descriptive psychologists of the Brentano tradition, whose value is nowadays recognised also by scientists like Fraisse and Michon (Husserl, 1966a; Benussi, 1907, 1913; Bonaventura, 1929; Calabresi, 1930; Koffka, 1935; Köhler, 1929; Fraisse, 1964; Michon and Jackson, 1985. On the topic see Albertazzi, 1998a, 1998b, 1998/99, 1999a).

The intuitive difference between phenomenological time and physical time is well known. In fact, all of us know the difference between the length of an hour spent listening to a boring lecture, or the brevity of a hour spent listening to an interesting one. Examples of this *elasticity* of phenomenological time abound in everyday life.

One of the most striking characteristics of quotidian experience is the fact – classically shown by the phenomenon of temporal displacement – that, in certain contextual conditions, the final perceptual outcome may differ from the effective sequence of physical stimuli (for example, Vicario, 1973, 1998; Pöppel, 1994).

This happens, for example, if the situation is too *emotionally* connoted, or if certain of the data in question have *greater phenomenic salience* than others (one colour being more *intense*, or one sound *louder* than others) because they catch our attention. The phenomenon is particularly striking if the elements are *temporally very close* to each other, so that they belong to *the same span of consciousness*.

To clarify this concept, I provide another simple example:

Take two intervals of *limited* duration, one delimited by *loud* sounds, the other by *soft* ones, for example, an *empty time* of *about 2 seconds* delimited by two metronome strokes. In this case, the interval delimited by the *loud* sounds will be *under-estimated* because the attention is attracted by qualitative factors (the loudness of the sounds). The intensity of the sound thus *alters the presentation of the duration of the interval*, which is lived as different. The same happens if the interval is delimited by *heterogeneous* sensations, like colours and sounds (already in Benussi, 1913; Albertazzi, 1998b).

Similar examples are plentiful in music perception, particularly in the dynamics between tonal and temporal distance, as happens in the grace note, in the tau and kappa effects, and in other experiments.

In particular, the *kappa* effect shows that *spatial distances* influence the perceptive evaluation of temporal intervals, so that the interval relative to the greater distance is perceived as longer. For example, in the case of three lights aligned horizontally in the sequence *a b c*, if the spatial distance between the stimuli is gradually altered, the central light is seen first as standing very close to the light on the left, and then as standing very close to the light on the right (Abe, 1936, but earlier in Benussi, 1907).

The *tau* effect, vice-versa, shows that *time* influences and alters spatial perception. For example, if two points of light are projected onto a dark background, in succession and with different distances between them, the greater

distance between them is perceived only if their temporal interval is increased (Abe, 1937, but already in Benussi, 1907).

Again, if points are flashed cyclically at the four corners of a square, at higher rates an apparently circular movement takes place. Evidently, in this case a fixed point is extracted which permits the representation of only one transformation (a continuous *rigid* rotation around that fixed point) instead of four successive ones (linear transformations which follow the trajectory: motion rightwards, upwards, leftwards, etc.) (Brown and Voth, 1937; Shepard, 1984; Grüsser, 1961).

The explanation for these phenomena is that *different modes of grouping* of the sensorial elements delimiting the temporal stretches are due to a different *qualitative* phenomenic *salience*: which means that, in one span of consciousness, the *perceptual whole* may differ depending on whether its *boundaries* are, so to speak, 'strong' or 'weak' (see Pöppel, 1994).

Another important concept to clarify for a perceptual theory of the time continuum is that of *change*. This is a key concept, one even more basic than the *before–after* relation. At bottom it means that *what* we present or perceive is less an *object* of a certain type, like 'flower,' 'Sol,' 'velvet,' etc., than essentially *a qualitative change* in one of the sensory fields of *sound*, *vision* and *touch*.

Moreover, the claim is that the perception of a qualitative change takes place even prior to the perception of simultaneity and succession (Bonaventura, 1929); in other words, that *recognition of change* precedes the *recognition of identity*, and that change is not reducible to the *before–after* relation as taken for granted, for example, in formal theories of the time continuum (van Benthem, 1991).

An empirical-experimental analysis of perceptual time addresses this problem as well – which philosophically concerns the *identity* and the *ontological status* of objects – on the basis of tachistoscopic research, working on the *microstructure* of the perceptual phenomena. This research, however, is only the scientific codification of phenomena which are very easily seen in everyday experience: for example, the *illuminations* that adorn our streets at Christmas time, or at a fun-fair, are in effect a variation of stroboscopic movement. I shall try to *synthesise the principles* governing these phenomena in an example (in fact, stroboscopic movement), concerning the temporal relations of *change, simultaneity and succession*.

Stroboscopic movement is an apparent movement which is perceived although there is no movement either in the physical world or at the level of the receptor organs: there is nothing in *physical* reality or on the *surface of the retina* to account for it (Wertheimer, 1912; Kolers, 1972).

With the tachistoscope used in a darkened room, the subject is exposed to *instantaneous* points of light at varying *distances*, at *varying intervals of time* – or, to points of light *moving along a certain* (variable) length at varying distances and with variables velocities.

What transpires from these experiments is that *below* a certain duration threshold (interstimulus interval from 100 msec to about 10 msec), the subject does not see, say, two single luminous points, but different renderings, and precisely:

- with an ISI of 10 msec, s/he perceives two lights in simultaneity
- with an ISI of 25 msec, s/he perceives some sort of flickering
- with an ISI of 100 msec, s/he perceives only one light moving from the first to the second position (beta movement)
- with an ISI of 50 msec, s/he perceives only a sense of motion, without figurality (phi motion).

Moreover, the *length of the interval* between successive presentations of the points of light is an *essential condition* for the generation of the *three* different experiences of *simultaneity, succession, movement*.

The experiment shows that in the passage from the perception of the *continuous movement* of *one single point* of light to the perception of *separate* and *successive points*, through an intermediate series, there is an *increase in the minimum time interval* that must elapse between the first and the last point for them to be perceived as successive.

In this case, as in that of perception of causality (see above, §3), there is a *difference* between what *physically exists* and what is *phenomenically perceivable*, which is partly different. In fact, the perceiver actually *sees something different* from what is happening at the physical level of stimuli, so that these experiments once again confirm that a *perceived succession* does not always coincide with a *physical sequence*.

These experiments consequently shed light on a variety of important features like the *perception of order*, *direction*, and the perception of *simultaneity* and *succession* in perceptual temporal continua (Hornbostel and Wertheimer, 1920).

A most important aspect is that these perceptual differences are essentially due to the *partition of the temporal intervals* and their actual perception (Benussi, 1913; Bonaventura, 1929. On this Albertazzi, 1998b).

The fact, moreover, that these apparent trajectories have no support in the physical world, but are seen as such, bears out the hypothesis of an *internalisation of the constraints* of the external world (Shepard, 1981, 1982).

9. Consciousness as a multifarious continua

At least one conclusion can be drawn from the examples presented: that some aspects of the nineteenth century neo-Aristotelian and empirical theories of continua have either been confirmed or have given rise to further analyses in the Gestalt school. These analyses are still in progress and are very relevant for the development of cognitive science (see Malik, in Russell and Norvig, 1995).

Most importantly, however, they yield evidence that the complexity in phenomena of perception derives from the *superimposition* of different types of continua. Here I have presented examples mainly to do with perceptual *space* and *time*, but 'actual perception' is given by phenomena from the various perceptive fields *embedded* in the spatio-temporal structure of the act of perceiving. For example, at a higher level of complexity, specific phenomena in the field pertaining to different temporal series can be defined as 'directions' of the continuum, as a finite, cyclical and in principle limitless series of the continuum itself (Husserl, 1988; Selz, 1929).

The other contributions to this Reading by scientists working in various fields of perception describe the characteristics of phenomena in visual, auditory and tactile perception as examples of the real 'boundaries' among *multiple* and *multiform* kinds of continua. The distinction, Brentanian in origin, is the following (Brentano, 1928/1981, 1976/1988).

We may consider a *multiple* boundary to be a region of space like the detached squares in the Aristotelian conception of a consecutive continuum (see above, §1). A *multiform* boundary, instead, is a boundary of a continuum which is *unitary* but *variously differentiated*, i.e., constituted by *non-independent parts*: for example, a 'seer' of a region of space, a 'hearer' of a sonata, a 'thinker' of something in the *moment-now* of actual duration. Further, an example of a 'multiple' temporal continuum is a series of sounds in succession; while an example of a 'multiform' temporal continuum is instead a melody or the simultaneous perception of that succession (Meinong, 1899; Benussi, 1913).

This last issue brings us directly to the problem of *consciousness*. As Brentano writes, "whatever intuits a continuum is itself continuous manifold (*Vielfaches*) – not a plurality (*Vielem*)" (Brentano, 1976: 43). Indeed, a multiform continuum is given by the *continuity of acts of perceptive presentation*: for example, two places that are not consecutive and which are independent of each other may be perceived together, and so on.

With respect to the theory of continua, therefore, the actual *acts* of *intentional reference* can be defined as *multiform continua*, existing in all their parts

and made up of connected parts. Inner perception, in fact, is the site of the original intuition of the continuum relative to a spatio-temporal 'something,' or event, 'filled' with qualities from the various sensory fields and which explicates itself as the perception of itself *qua* multiform continua. In other words, there is no 'first-person' perspective, in intentional reference (Albertazzi, 1998a, 2001a. This point of view is also maintained in Buddhist logic. See Stcherbatsky, 1962).

The implications of this kind of experimental metaphysics as regards internal representation can finally be summed up in a theory of intentional reference, whose main tenets are the following (Brentano, 1874/1973; Albertazzi, 1999b):

1. The intentional presentation manifests to consciousness, and in evident manner, the perception of a *boundary*, and of a *qualitative form* derived from the perceptive continuum. In short, the 'things' of Brentano's metaphysics are *objectual forms* that can be primarily identified on the basis of edges, corners and zones with high chromatic contrast and brightness (for an experimental development of these aspects see Palmer, 1999, in part., Ch. 6 on connectedness and regions).
2. *Time* and *movement*, like time and *geometric shape*, are co-variable. There is no monotonic psychic state, and variation in the velocity of the presentation of sensations gives rise to dynamic inner forms, examples being stroboscopic movement, temporal inversions (see §7), or Michotte's experiments on the perception of causality (see §3). The complexity of perceptive forms therefore arises from their *unfolding on a temporal series* of perceptual successions.
3. Whether a sensation concerns an essentially temporal object like a melodic sequence or a trill, or whether it is the visual perception of a landscape, a statue or a painting it has a *temporal structure* – the persistence of which is signalled and maintained in the temporal dimension of the duration.
4. Information on the world (as inner presentation) consists primarily of a constant relationship among the multiple and multiform continua of perceptive experience, the intensity of the sensory qualities of the continuum, and their energy as computed in quantitative units of measurement.
5. Since the sensory qualities are produced by the nervous system, the intentional presentation is but an *index of variations in the stimuli* and a *qualitative measure* of the material determinations.

These aspects of a Brentanian metaphysics seem to be consistent with the findings of contemporary research; and specifically that the quantitative measurements are translated into a frequency code which operates on temporal inter-

vals so that, as Brentano theorised, the more intense the sensory quality, the denser the relative temporal series. Secondly, the 'objects' (not actually existing 'things') of which successively we speak according to a principle of identity – largely the outcome of *mental constructs* or cognitive completions – which stabilises their characteristic notes according to a principle of invariance, are such relatively to a *space of re-presentation*, thereby confirming hypotheses first advanced by Husserl and successively by Musatti (Husserl, 1913; Musatti, 1964. See also Shanon, 1993).

These are the outcomes of the theory of intentional reference from the point of view of the perceptive continua, at least in the first instance. Detailed descriptive and experimental analyses taken from the perceptual fields, as the other contributes to the volume show, may contribute to support this point of view, as different modes of *participation* of the 'phenomenal self' in 'phenomenal objects' (the expression in Duncker, 1947).

Notes

1. 'Empirical' is intended in Aristotle's and Brentano's (1874) sense of descriptive analysis of experience.

2. The figures in electronic format were reproduced by Mario Callegaro. Fig. 36 is due to Osvaldo Da Pos.

3. Fig. 27 and 40 are reproduced by kind permission of Stephen Palmer and Mary Peterson respectively.

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CHAPTER 2

The edges of images

Considerations on continuity in representation

Ruggero Pierantoni

1. The biology of smoothness

When the human body works perfectly its owner enjoys a series of exalting sensations. The power and the grace of the jumper, the fluency of the swimmer, the deadly precision of the boxer, the delicacy of the lover: all these actions share a common element, namely continuity. The sudden interruption of the act of walking, the jerky motion of a limb, the unsteadiness of the fingers, the inaccuracy of the hand which fails to grasp an object: all these conditions are feared, and counteracted by humans with all the means at their disposal. We know that continuity in movements, smoothness in actions, co-ordination in complex behaviour means survival and victory over other, less 'smooth,' competitors. In short: continuity has strong evolutionary value and the entire muscular and skeletal architecture of our bodies is designed to enable a mass of about seventy kilos to move about without too much awkwardness.

At the same time, the objects and organisms that move around us seem to prefer smooth movements, continuous streams of motion, stable trajectories. But 'smooth movement' means, biologically speaking, predictability. And predictability implies victory, the elimination of the less fit, cancellation of the adversary, precedence at the banquet. It suffices from this point of view to remember that we humans (and non-humans) are equipped with a complex system of motion, velocity and acceleration detectors all integrated into functional pools of neurons, the output of which is the muscular response to the basic information termed 'time to impact.' Computation of the 'time to impact' enables the organism to dodge what it wants to avoid or hit what it wants to kill. And the computation must be carried out in real time, for otherwise we suffer the social accident that the French aptly call '*esprit de l'escalier*.'

However, objects and organisms do not always move in smooth and predictable fashion. We filter out only those that move in a way that we may have to cope with, and prefer to ignore the others. We sense the filter in action when trying to catch a fly in free flight with our hand, for example. In short, we pay attention to objects and organisms with a significant mass and which consequently obey the law of inertia. A mass left alone and not subjected to any force will remain immobile or continue its course along a linear trajectory, maintaining its velocity constant in intensity and direction. This again means perfect predictability. But things in the real world apparently do not respect Physics 001 classroom exercises. Frictions, turbulence, dishomogeneities of all kinds, thermal gradients, irregularities in the distribution of masses, combine to introduce the disturbing forces so unloved by the average physics student (level 001 and above).

Consider the complex trajectory followed by a leaf as it falls from a tall tree. Those who are not as intelligent and subtly but anomalously minded as Forrest Gump very soon lose interest in it. This almost instantaneous disinterest in falling leaves or flying flies or unstable jets of waters is, in reality, highly indicative of the evolutionary irrelevance of such 'insignificant' events. One must be a very keen observer or a 'poet' to waste time on following such uninteresting minor phenomena. And the very fact that an extremely small number of humans find interest in the irregular movements, unpredictable trajectories, jerky motions of objects or organisms says a great deal about the limited importance of this curious cinematic. And, when did you last see an inanimate object moving around with jerky movements? One of the few such objects (certainly not inanimate) are 'Mexican beans' which, left alone on a table, jump with extreme determination. But we know very well why they do so.

2. The invisible leaping frog

I shall now consider in some detail the movements made by animals when they undertake an action. Consider, for example, the jump of a frog. The action roughly divides into three phases: accumulation of energy, its release, passive motion. The first two moments are extremely rapid and they may easily go unnoticed. The frog executes very small and almost secret movements with its hind legs and sets its torso and head in a particular posture. These preliminary movements are very like those performed by a pianist before s/he starts playing. Then the actual, dynamic jump takes place, and it is the only noticeable part of

the leap: the phenomenal part of it. During the jump, while the frog is in flight, it extends its forelegs and prepares its body for landing.

Now, we know what we see, or at the least the better we see the better we know. Hence from our common experience, the jump of a frog is a continuous motion which strictly follows the laws of dynamics; and the laws of dynamics can be written using a conventional system of symbols which imply continuous variations in the related parameters: time, space, and their relative functions. The very fact that we humans have devised a complex linguistic system of highly abstract symbols and defined their enormously complex relationships simply means that we have created a representational system able to cope, at least from the phenomenological point of view, with the visual phenomenon. And this representational system relies on a notational system in which the independent variables have the computational property of analytical continuity. Another link in this never-ending chain is the complex of properties possessed by the set of natural numbers, with its intrinsic dichotomy between the discontinuity of the digits and the continuity of their fractions. As a simple consequence, any, even very simple and rough, mathematical 'rendering' of the jump of a frog contains the elegant linguistic paradoxes of Zeno of Helea.

The postulate of the continuity of the categories of time and space (and, more cogently, the coherent creation of the set of natural numbers) finds its origins and roots in the jumping of frogs, the falling of stones, the motion of stars, the smooth glide of waves, the oscillation of fruit, the regular billowing of sails and flags. But when we decide to come to terms with flies in flight, the breaking of waves, the edge of crystals, falling leaves and the reflection of the moon on troubled waters, we feel an urge to invent new sets of numbers, alternative geometries, a different representation of space, and perhaps to forge a new time.

3. Wavelets and 'clicks' on old records

Non-linear mathematics is a new discipline, and its main purpose is to harness discontinuity: jerking numbers, fragmentary dimensions, fuzzy boundaries among sets, quantal frogs. One of the most interesting and powerful products of this new mathematics are 'wavelets:' a recently-developed instrument which enables one to see and represent sudden discontinuities in the domain of images. The merits of 'wavelets,' of course, are not confined to the visual domain; they extend, more than naturally, to the acoustic one, where they enable us to 'see' timeless modifications in the pitch, intensity and phase of acoustic

events. They are, in sum, the completion of Fourier's analysis, which is linear in its intrinsic nature. But the non-linear side of temporal phenomena is immensely significant and its domain has been overlooked for too long. Wavelets help us to visualise an invisible and hitherto unknown world of instantaneous, discontinuous, almost diaphanous phenomena. In order to appreciate the deep mathematical meaning and, at the same time, the more than 'mundane' application of the Wavelets Transform (WT), we may consider a classical, though rather annoying, case of discontinuity.

There has been a recent revival of interest in old music records. Almost unknown and priceless recordings of musicians and singers are retrieved from the archives, but they are very often flawed by 'clacks,' 'clicks' or other acoustic disturbances caused by mechanical damage to the record. The elimination of clicks has been impossible until now because they are typically bound by energetic parameters which prevent any repair: low energies, very short duration, impulsive quality, and spectral components in the very high frequency range. WT enables the treatment (i.e., detection, elimination and substitution) of these undesirable features (Tuzman et al., 1998). The mathematical treatment of discontinuities, though intended mainly to eliminate them from the final acoustic pattern, sheds new light on the nature of discontinuity in general. And this new light can be extended, almost unchanged, to the realm of visual representations, to which WT and other mathematical treatments can be straightforwardly extended.

Before leaving the subject it should be pointed out that the acoustic discontinuities preventable with the WT technique were not intentionally introduced into the representational space of musical events, but they are nonetheless real discontinuities. In order to generalise this point to the visual and plastic arts, consider a typical work by the Italian painter and sculptor Fontana. This artist, in a certain period of his life, produced numerous canvases painted pure white, and with a sharp cut and nothing else on their surfaces: a classic case of discontinuity, but one performed intentionally. We may define Fontana's 'cuts' as visual clicks; or clacks if you like. But they are intentionally introduced discontinuities whose inner nature can only be grasped, formally speaking, by using the tools of differential topology. Some years ago the French mathematician Renè Thom achieved great personal success by re-introducing Poincarè's analysis of topological instability into mathematics. His *Thèorie gènerale des catastrophes* was a best-seller comparable with D. R. Hofstadter's *Escher, Gödel and Bach* (Thom, 1968; Hofstadter, 1968). It is of interest to note that these two exemplary and opposite books were centred on the philosophy of continuity (*Escher, Gödel and Bach*) and discontinuity (*Thèorie gènerale des catastrophes*).

4. The gesture as the filter of continuity

After the foregoing brief discussion of a relatively recent mathematical implementation for the acoustic representation of discontinuous phenomena, it is advisable to take a further step back. As an example of a continuous motion performed by an organism I have chosen the jump of a frog. In this case the action, the actual motion (or movement) is a 'real fact:' the frog has really jumped from here to there. But in some cases, animals, and humans, are able to do more: they can pretend to move. They make gestures. It is certainly very difficult and almost pointless to try to define a 'gesture.' But a working definition might be the following: a drastically abridged act which fails to accomplish its original and usual goal but which retains significant components of its original dynamics.

One need only to watch two kittens at play to recognise 'gestures' among their numerous 'movements.' Many of these 'gestures' are 'caricatures' of the related movement, but they are still true movements, and even if the kitten does not 'intend' to harm its adversary, it acts as if it wants to. The gesture displays ellipses of the 'real' execution, an accurate filtering-out of components, which are eliminated from the gestural action, an emphasis on some altogether minor linguistic component of the whole action, and it almost always eliminates the conclusion. A gesture is a highly complex behavioural event and its relationship with the original and complete action is intricate and often contradictory.

At this point it may help briefly to consider some elements of 'Labanotation.' The German dancer and choreographer Laban created one of the most intricate and detailed notational systems for ballet. It has been noted since the seminal essay by Nelson Goodman, 'The Languages of the Arts,' that ballet is a classic case of the profound ambiguity between the 'arts of space' and the 'arts of time.' Its intrinsically dual nature raises immediate difficulties for a system of description or 'notation' able to furnish the dancer (and the choreographer) with spatially accurate, temporally organised and anatomically coherent information and instructions on how to perform on a particular occasion. The solution adopted by Laban in 1934 was to describe in detail, and occasionally with the help of schematic drawings, all the positions and 'expressions' of the body. In complete opposition to the classical Russian-French tradition in which the dance movements were taxonomically described and followed a rigid syntax, 'Labanotation' concentrated on the 'psychological contents' of the acts represented. For example, the dancer had to be able to convey the impression of an individual who was "very humble but defiantly proud and potentially danger-

ous" or one "expressing profound grief under the mask of apparent gaiety" or similar extremely complex and self-contradictory states.

This entails almost unbearable concentration by the dancer, who must use all the means at his/her disposal to produce the result. Less considered is the transition between 'profound grief' or 'shameful humility' and the next moments in the narrative. This is a major syntactic problem in the classical dancing tradition as well, although in this case it is felt much less forcefully because the 'positions' are quasi-abstract and mainly convey figural and static-dynamic features which are not always the 'bearers' of psychological or mental states. The passage from the third position to the fourth is complex and must be accomplished with great precision, but it raises fewer problems than does the passage from 'restrained wrath' to 'overt rage.' But, in one way or another, it is clear that a dancing action is a temporal 'collage' of 'tableaux' connected together by the clever use of formalised 'transitional states.' At first sight, it may appear contradictory that the dancer's space is, or at least 'appears' to be, continuous while his/her movements must be discontinuous.

We have a very compelling descritpion of a "pre-Laban" performer from the acute eyes of W. Goethe. He was in Naples and vicinities during the beginning of March 1787, many watercolours are dated from this period: the CG II, inv. 1114, CG II, inv. 353, CG, II, 112, inv. 340. Some of them are accompanied by a brief text. In particular we may remember the first two: "The sea storms of the last days have shown us a beautiful sea, we had the opportunity to study the waves in their monumental form and image", "If I am imposing to myself to write words, there are always images that appear in front of my eyes . . . " This was a peculiar moment in which Goethe was interested in the representation of movement, both very fast as the waves, or quite slow as in the smoke of the erupting Vesuvium. But his keen observations and drawings of the "Serapeum" and his graphical "reconstruction" of the progressive vertical up and down millenary movement of the monument witness for us his interest in the invisible or non perceptible movements. He had the opportunity to visit the English Ambassador Sir. William Hamilton and his young lover, the so called Mrs. Harte (her true name was Emma Lyon). Among her many talents she had the ability to change continuously expression, pose, clothes. Here some lines from the bewildered Goethe: ". . . she continues to change pose, gestures, expressions etc. At the end it seems you are dreaming. What could have inspired many thousands of artists is for us a reality in motion, in a surprising succession of postures. Standing, on her knees, sitting, laying down, sad, mischievous, unbridled, penitent, menacing, timid and so on: one expression follows another, and the new comes to substitute the former one . . . ." (Caserta, 16th March 1787).

If we have in mind this "scientific" description of Goethe we may understand better the intention of Hugh Douglas Hamilton (1736/1739–1808) the painter who produced around the 1789–1790 a triple portrait of Emma Hamilton. She is represented three times in three different attitudes which have to be read as three Muses but, to our eyes, it remembers a triple exposure photograph not different from the futuristic images of Russolo or the multiple portraits of Duchamps.

5. Hercules between Vice and Virtue

In an impressive and amusing analysis of a painting depicting 'Hercules between Vice and Virtue,' Ernst Gombrich conducts detailed study of the precise moment which the painter sought to represent. The hero is approaching a point where the road that he is following branches in two directions: along the right branch there stands a gentle lady well and decently clad. But to the left awaiting the hero is a quite different creature: a voluptuous, dissolute, half-naked, evil (but beautiful) creature. Where will the hero go: to the right or left? The painter very aptly chose the moment of approach, not the one after the decision. He was faced by a quasi-infinite range of choices, but at the moment of representation this apparent infinity reduced to a handful of 'tableaux.' The painter had even fewer possibilities than the colours on his palette: three or four, no more. A painter is therefore in a very different position from that of the mathematician trying to write the equation of the jumping frog. Whilst the frog's equation will 'honour' the entire event from start to landing, the hero's image in painting will catch only one frame of it. In fact the analytical treatment of the animal's movement is perfectly 'represented' by the equation which explains and quantifies its every moment. Mathematics is more democratic than iconography: why is this so?

To answer the question we may for the moment abandon meaningful events like 'Hercules between Vice and Virtue' or 'Paris and the three Goddesses' or 'Hamlet Confronted by the Ghost of his Father,' or even a typical 'Crucifixion,' and try to think how a painter would cope with a subject of much lesser importance: 'The Jump of the Frog.' Physics handbooks provide us with dynamic elements which may help us in setting the scenario for our frog. The frog's jump will follow a parabolic trajectory, with its maximum acceleration (i.e., variation of speed with time) at the beginning and at the end. The top of the trajectory is the highest point in relation to the ground and it is characterised by a minimum of acceleration, while the speed briefly settles at a steady

value. At this point the velocity vector maintains its numerical value and direction for a short time. So far we have considered the frog as a whole, and we have followed only its centre of gravity during the jump. But during the leap the frog has changed its bodily posture in many ways: contracting and retracting its legs, changing the angle of its head in relation to the thorax, even opening and closing its mouth during an optional croak. Before photography, human eyes had never registered all the events now described, including the movements of the frog's limbs during the leap. Evolution did not bother to provide humans with accelerator detectors working in a range very rarely attained by the objects and organisms moving about us. A classical consequence of this 'defective equipment,' as far as detection of acceleration is concerned, is the impossibility to see in detail, and as a consequence to represent, the galloping of a horse. The simple but very interesting fact is that for at least 4000 years galloping horses were always represented in the same way, with some minor variations: the animal was drawn with its fore and hind legs fully extended. Since 1887, the year of publication of Eadwear Muybridge's eleven-volume work *Locomotion in Animals and Men* (Muybridge, 1887), we know that the position of the extended legs is only one of the many highly complex anatomical attitudes taken up by a horse as it gallops. The subjective 'invisibility' of the majority of these attitudes depends, not on the presumed excessive velocity of the animal, but on the complex patterns of continuous acceleration and deceleration of the four legs in a reduced visual space. The net result, helped by such mundane circumstances as the shape of the objects upon which the image of the galloping horse was projected, was a filtering-out of all the 'intermediate positions' to leave only the final image with the legs fully extended. The reason for the selective filtering to produce this posture alone was its relatively stable visual quality while all the others had to cope with the intermingling of the four legs in a confused and highly mobile pattern. If, we now return to the leaping frog we find that the only moment when we can actually see and memorise the little creature is the highest point in the trajectory, when the animal 'flies' with its fore and the hind legs fully extended. This, in fact, is another example of the radical filtering of a single 'frame' among many other ones from the invisible film 'The Leap of the Frog.'

6. And the hammering Ephestos

I wish to add a second and a more elaborate example of the filtering process in order to highlight the cultural complexity of the problem. It is necessary to

realise that the breaking up of the continuity of perception into the discontinuity of images is not only the effect of the limitations of our visual system. Such an 'explanation,' in fact, risks explaining absolutely nothing and creating more problems than solutions (for more detailed analysis of the pictorial representation of movement and these cultural mechanisms see Pierantoni, 1986).

I shall take as an example another classical scene: the visit of Thetis to the Vulcan's workshop. The mother of Achilles, anxious to protect her now vulnerable son, goes to Vulcan to ask him to forge a new shield. This is a typical occasion for the painter to demonstrate his ability to deal with a 'transcendental' difficulty. The main problems at stake are the representation of the fire, the optical qualities of the polished and convex metal surfaces, and the perfect rendering of the tensional state of the muscular torso of an aged yet vigorous man. In almost all cases Vulcan is positioned while hammering a block of red-hot metal on his anvil. His right arm is raised high above his head, and he firmly grasps the hammer, ready to strike. The painter must deal with the distributed tension of almost one hundred muscles, and this is the reason (or at least the linguistic reason) why Vulcan wears only a loin-cloth or little more, so that his muscles can be exhibited and depicted. I have no knowledge of any image of Vulcan with the hammer at the end of its stroke.

It is evident that filtering the moment of the beginning of the stroke out of all other possible passages is a quite complex solution of a multivariable cultural and technical equation. Philosophical backgrounds and linguistic scenarios may have interfered with the choice of the image because the potentiality of the act is considered to be of greater cultural weight than representation of the completed action, when viewed in Aristotelian terms. Technical ability and aesthetic considerations may have stabilised and perfected the solution because the appearance of muscular tension was considered more 'beautiful' under these rather than other conditions. The model's necessary immobility in the initial position is easier to achieve and maintain for a long time, or at least for the time required by the painter to sketch the main features of the muscular patterns. The perceptual stability of the 'high position' may have prevailed for a simple reason: the whole action is practically invisible except at its very beginning. In the volume on 'The Human Figure in Motion' in Muybridge's book, plate 84 of the 1955 abridged edition by Dover publications is devoted to a 'Carpenter cleaving with hatchet and hammering.' From the series of the images one can calculate that the entire striking movement lasts much less than one-sixth of a second. In fact, the nine-frame sequence does not show the details of the stroke: only the initial position in the first frame and the cleaving of the wood already in the second. This particular subject, given its intrinsic inter-

est, is treated in some detail in the Addendum, which gives more quantitative treatment of the subject with the implicit proviso that the sensory and perceptual treatment does not 'explain' the iconography of the scene but is meant only to add a small *tessera* to the overall mosaic.

7. Illusion versus continuity according to Wickhoff

With the cautious proviso that the filtering of the perceptual world into a discontinuous set of images may depend on cultural ecosystems and is not just a passive and deterministic outcome of the limitations of the visual system, we may turn to a prophetic statement by Franz Wickhoff. In his extremely original analysis of Roman sculpture, *Römische Kunst*, originally published in Berlin in 1912, Wickhoff writes: "The new art, instead, chooses from the totality of the real world only what it is particularly apt to represent illusionistically the perception of its appearance at a given moment." He contrasts 'new art' with the 'old art,' which "...tries to reach its goal through the organic and essential reproduction of the object or the person the artist intends to represent." We have here a further contribution and a further complication as well. Not only did Wickhoff understand very well that the world of images has profound discontinuities, and that they depend on some "appearance at a given moment in time," but he realised that representations of such 'visible instants' are rendered 'illusionistically' and not 'organically.' Wickhoff illustrated this critical point with examples of 'illusions.' Among his contemporaries, Wickhoff had been exceptionally interested in the French impressionists, and he had first-hand knowledge of Dutch and Flemish painting. On many occasions he used examples from these periods of art history to illustrate a point in his interpretation of the main features of Roman art. In the second chapter on "Augustan Art," he writes:

> From the drawings of the Flemish artists, mainly from those of Rembrandt, we may learn that it is possible to reach a complete illusion with five or six little points or detached segments which are appropriately located within the simplified boundary of an head (Wickhoff, 1947: 14).

And later, when he carries out comparison with Etruscan sculpture, he adds in the same vein: "In a head synthetically rendered the sculptor inserted the characteristic 'Gestalten' of the single part of the face. These ones, when seen at the right distance, astonish the beholder with their illusion of life."

We can now understand what Wickhoff meant by his use of the term 'illusionistic.' The "distinct tracts or separate points," or the "synthetic features of the face," are not the precise and organically complete, isomorphically coherent counterparts of the living organism but an abridged, yet significant, form of the model. These 'signs' are reminiscent of the above-discussed gestures whose main content is still the core of the movement that gave them birth. But the structure of these representations is illusionistic. We need dwell no longer on the critical importance of this 'illusionistic' procedure since the exhaustive and seminal book by Ernst Gombrich, *Art and Illusion* (Gombrich, 1958). But if we consider the original title: *Kunst und Illusion. Zur Psychologie der bildlichen Darstellung* the close proximity between Gombrich, Wickhoff and Riegl is evident. And the illustration chosen by Gombrich to comment on the illusionistic rendering of the fabric of the mantle worn by the subject in Rembrandt's *Burgermaister Jan Six* exactly complements Wickhoff's remarks on the discontinuity of the painting action (Phaidon-Köln edition of *Kunst and Illusion*, 1967: 371; Bild: 267).

This digression has brought us back to the gesture, but with a significant difference: a pure gesture disappears after its end and nothing remains of it except in the memory of the beholder, or in some mechanical or electronic device. But a gesture executed on a substrate becomes a sign. The formal and solemn dress of Rembrandt's Burgermaister is rendered with a series of distinct and neatly separated brush strokes. The deliberate discontinuity injected into the painted surface has no direct relationship with its physical counterpart but stands in a dialogic state with its visual one.

8. Johannes de Eyck fuit hic 1434

As an opposite example of the "isolated tracts and coloured dots" described by Wichkoff with regard to the Dutch painters with their implicit discontinuity we may now look at a champion of perfect continuity: Jan Van Eyck.

His *Arnolfini's Marriage* or the *Madonna of Nicholas Rolin* or the Dresden Triptych present the beholder with a perfect surface where the very act of painting is untraceable even in its most elemental atoms. The painted surface resembles a perfectly transparent and polished window through which our gaze penetrates into a further, miraculously detailed and visibilised world. The reasons to pursue this total visibility using all the 'magic of painting' stem from a complex mixture of religious, rhetorical and superstitious attitudes and intentions. One of the most evident consequences of the continuity attained in

the representational space is total cancellation, the 'invisibilisation' of the act of painting. In a certain sense the painter is more present in Van Gogh's *Vase of Sunflowers* than in the vase of lilies standing in the foreground of van Eyck's *Annunciation* in the National Gallery of Washington. Indeed, van Eyck's magical ability in painting was so unusual that "the painters were considering his works in dismay and in mute stupor," as C. van Mander wrote in 1604. For the moment it may suffice to consider that the invisibilisation of the act of painting is equivalent to the invisibilisation of the painter's gestures. These absolutely perfect surfaces annihilate the painter and his presence and they stand for themselves: they are not created. This perfection has been pursued and eventually attained under the pressure of numerous cultural forces. But we must restrict ourselves to a single path: the one that borders on continuity at one side and on discontinuity at the other. And we may gain more penetrating insight into these impenetrable surfaces which will soon appear as tri-dimensional labyrinths for the ambient light.

Even these crystalline masterpieces, with their absence of human action and their negation of the processes that engender them, hide the secret of their essence: discontinuity. Only quite recently and by means of sophisticated technology have we discovered a part of their 'magic.' In her careful and documented study on the pictorial technique of the early Dutch painters, M. C. Galassi has shown that the 'Flemish primitives' produced their paintings by means of a complex technology (Galassi, 1991).

They began with bases of perfect white upon which, with charcoal or a pencil moistened with ink, they traced an accurate drawing of the future painting. When made visible by infra-red reflectography, this drawing reveals a highly accurate texture of highlights and shadows. But on other occasions the drawing is sketchy, and the figures, their clothes and the objects that they hold are rendered rather coarsely. In particular, the shadows are drawn using the classical chiaroscuro technique of cross-hatching. Only now does the painter begin to deposit layer upon layer of perfectly crystalline, transparent yet coloured glassy matter. Each layer is directly illuminated from above by ambient light, and indirectly from below by reflected light which must pass through all the layers before reaching our eyes. Each layer contains pictorial matter which completes the incompleteness of the underlying drawing. At each layer we pass from discontinuity to continuity until, at the last and most superficial layer, the underlying drawing is completely obliterated by the perfect image. Yet this 'image' is not to be found anywhere because it is an integral to our visual system of a series of 'provisory' images.

Galassi points out that this immensely sophisticated representational technique has a very mundane purpose. The Flemish painter's atelier is an industrial complex where all the energies, skills and experiences of the head painter's assistants are concentrated on the steady production of a large number of quality products. The drawing was the basic module of production and it retained the qualities, ideas and gestures of the master painter. The large number of extremely competent, obedient and patient collaborators undertook the work of flawlessly completing the painting (Galassi, 1991).

9. The apparent continuity of the ribbon of time

After this discussion of the completeness and visual continuity, but material discontinuity, of Flemish paintings we may return to Wichkoff and his analysis of the temporal continuity of the narrative stream of complex histories. We may now individuate the roots of the breaking-apart of the continuity of the narrative into the discontinuity of the representation. We have seen that, for many reasons, even at the purely sensorial level, Ephestos' arm is represented high above the anvil and not at the end of its course. At the same time we may discover why such a highly complex and 'continuous' stream of events as the war against the Dacians has been frozen into a large number of 'stills.' A cursory look at Trajan's Column shows how this technique of 'historical sampling' has been devised and applied on an immense scale.

We may start with a detail of the scenes (XVI–XVII–XVIII: 39–41). The numbering of the images follows the most accurate and modern edition of the Column (Settis, La Regina, Agosti, Farinella, 1988). In this 'scene' Trajan surveys the building of an encampment. In the background a soldier with a hatchet is depicted in a position almost identical to that of Muybridge's model. But, if the single figure has been sculptured following a long-standing tradition, which may have some of its rationale in a perceptual sampling of the world, the whole composition extends its roots into a far more complex system of ideas.

The following considerations are taken mainly from the fundamental study by S. Settis, "La Colonna" (Settis, 1988: 45–241). The main aim of this work is to show the complex syntactic strategies used to narrate the Dacian wars. The basic contradiction is the apparent opposition between the continuous nature of the sculptured frieze and its internal division into chapters, scenes, actions and presentations of individual persons like Trajan or Decebalus or the choral presence of their armies and the population swept up by the war. The mechanical continuity of the frieze, which is aptly paralleled with the 'rotuli'

and the triumphal pictures, is modulated by a system of 'caesurae,' intervals and breaking points. These elements have a primary function of separating adjacent scenes through the use of a figural landmark: walls, trees, bridges, fences and other 'separating or connecting' objects. But the subdivision of the 'rotulus' into narrative modules is only one of the many rhetorical devices used. The following three types of reading are suggested by Settis:

Sequential reading. The reader follows the entire narrative from the siege and capture of Sarmizegetusa to the end of the war and the symbolic 'herd parade.' The complex takes the form of a single, complete narrative to be read continuously from beginning to end.

A1. Each 'chapter' may be read as an isolated, though narratively complete, unit characterised by a beginning, a central theme and a concluding image.
A2. Starting from a 'focal point' it is possible to explore the scenes, which are contiguous to the chosen starting element and follow the narrative stream both up-time and down-time.

Reading 'by waves.' Starting at any point the reader searches through scenes or 'topoi' internally related by affinities: camp life, battles, acts of clemency towards defeated enemies, and so on. Or s/he searches for individual scenes, the 'hapax legomena' like the suicide of Decebalus or the 'discovery of the Dacian treasure.'

Random perception. The reader does not follow a strictly narrative 'usage' of the column but allows his/her eye to move freely along the shaft vertically or spirally, or to jump from scene to scene. Even when no deliberate reading strategy is followed, the sequence of images is so closely interconnected that parallelisms, assonances, similarities, visible metaphors constantly appear and disappear.

It may be of interest to consider the complex syntactic devices that surround a key episode depicted by the Column: the suicide of Decebalus and of some of his closest associates and soldiers. This famous scene is at the centre of a system of symmetrical episodes which anticipate and comment on the central one. It is possible to link all the scenes from no. 209–219 (Bellum) to no. 237 (Salutatio imperatoria). This figural system of sequential images reaches its emotional climax in scene no. 226–230 (Mors voluntaria).

Trajan's column shows that a figural sequence in mechanically continuous form may be internally structured into modules, and that these modules enable the beholder to move freely up-time and down-time. This exploratory movement involving a mechanical activity by the beholder is a real gesture executed

during the active perception and exploration of this cultural echo-system. In this case an objective, external, mechanical continuity is broken down into sub-units and made discontinuous by a sequence of gestures executed by its explorer. Trajan's Column cannot be considered typical of any image whatever because it was deliberately intended to represent a series of events organised through time. The bases of the Column represent the beginning of the first Dacian war and the last image, the 'herd parade,' the end of the second.

We may now consider a quite different example: the Phydian frieze of the 'Panathenaics' which is intrinsically organised into a horizontal sequence whose complete exploration requires a corresponding physical response from the beholder, who must literally walk along it to see the entire sequence. The Athenian citizen who wanted to view the entire frieze had to follow it because of its horizontal arrangement, thus repeating and replicating the actual walk of the kouroi and the korai. This is another clear example of a behavioural act induced by a continuous visual and cognitive stimulation. But the intrinsic difference between the Parthenon's internal frieze and the column's external spiral is that the latter depicts a piece of history and the former an 'eternal' act of foundation of the city. But a Roman citizen who wanted to see over and over again the Emperor Titus at the head of his quadriga under his triumphal arch had only to stand under the arch itself and observe, motionless, the immobile passage of the imperial 'quadriga.' The beholder had only to immobilise him/herself exactly as s/he had done during the actual triumph and see what, by pure chance, had happened as seen from his/her occasional vantage point.

10. The discontinuous gesture of the eye

For a complex fresco like the one painted by the Lorenzetti for their Palazzo di Città in Siena, and where the arrow of time is not made explicit, the act of reading becomes an act of seeing. The eye is free to explore the immense surface and is guided in different directions, constantly changing its information-gathering strategies from one location to another. In this case the dominant element is the exploratory behaviour of the eye as determined by the neuro-muscular hardware. But since Alfred L. Yarbus' classic study, *Eye Movements and Vision* (Yarbus, 1967), it has been entirely clear that it is the pattern and image being looked at which governs the eye's dynamics. The physiological machinery is entirely at the service of an organised exploratory cognitive behaviour the purpose of which is to extract the maximum possible information from the

visible environment. This is tersely stated by Yarbus himself at the beginning of Chapter VII, "Eye movements during perception of complex objects":

> The study of such records as these suggest mainly that, when examining complex objects, the human eye fixates on certain elements of these objects ... Analysis of the eye-movement records shows that the elements attracting attention, in the observer's opinion, may contain information useful and essential for perception (Yarbus, 1967: 46).

The immediate consequence as far as we are concerned is the filtering of a continuous scene in a cluster of fixation points from which the main information is gathered. But this filtering applied to naturalistic vision may be helped or somehow anticipated by the artist when he produces a representation of the environment. The act of representing objects, organisms and their locations on a surface or on a volume may be, as Wichkoff has put it, 'naturalistic' or 'illusionistic.' Even if we contemplate a perfectly accomplished painting of Jan Van Eyck, we filter, smooth, eliminate and mask. In a sense it seems that the superhuman ability and painstaking concentration necessary to produce these perfect 'illusions' has been wasted and useless. In fact the same effect may have been obtained through more economical means. A short passage in Wichkoff describes the extraordinary illusionistic power of the Pompeian paintings: "The transparency of the glass, the silky splendour of the skin of the asparaguses, the velvet of the peach, the soft humidity of the cuttle-fish [...] all are obtained with few and separated brush strokes [...]." This is a veritable hymn to discontinuity in representation, and it is certainly in cultural harmony with Yarbus's observations. I merely comment on the two quotations that image-makers, even the unsuspicious 'beeldemakers' of Jan van Eyck's times, have always worked in anticipation of the beholders of their images. Their gestures have been the first links in the chain of discontinuous events into which they melt the illusory continuity of the 'real world.'

11. Addendum

As already stated, vertebrates and invertebrates are equipped with motion detectors and velocity detectors. In general, the velocity of a moving object is computed according to the displacement of its image on the retina surface. These 'detectors' are neuronal complexes whose output is sent to progressively higher levels along the visual pathways. A characteristic of these neuronal pools is their limit of fusion: that is, the velocity at which the subject is no longer able

to see the details of the moving object. Under different experimental circumstances the fusion takes place over a range between 12 to 32 degrees of visual angle per second. Therefore, when an image moves across the retina at a velocity within that range we are able to sharply distinguish the image of the moving object from the background. The reasons for this functional limit are many, but the essential point is that, under these limiting circumstances, the perceptual machinery has insufficient time to build the percepts of the visual edges, so that the resulting image of the moving object is blurred. This characteristic boundaries to our visual system was the main reason why Galileo devised different and very ingenious ways to reconstruct the parabola of a free falling object.

But velocity is one thing and acceleration is another. It is well known that acceleration is the variation of velocity over time. The presence of acceleration detectors has not been explicitly demonstrated, but certain studies have been able to evaluate the threshold for detection of minimal acceleration. In order to follow the argument it may be useful to remember that the hammer of Ephestos is immobile at its highest point. It is then subject to its greatest acceleration, which gives way to a quasi-constant velocity. At the moment of striking, the hammer is travelling at great speed but its acceleration has significantly decreased.

From Muybridge's images we may deduce that the complete course of the hatchet held high over his model's head in the first photograph will last no longer than 0.166 of a second. In fact, the interval between one image and the next is almost exactly 1/6 of a second, and the entire movement is accomplished within only one frame. The hatchet had completed an arc about 1000-mm in length in 0.166 seconds of time. In order to know the speed with which the hatchet's image moves across the retina we must give its distance from the observer. This is an arbitrary value but we may use the distance of the camera from the model, which was 3 metres. Skipping the technicalities, we may calculate that the image moved across the retina of this observer for 5.6 mm. at a speed of 100 degrees of visual angle/second. Had the hammer's image travelled across the retina at this speed we would have seen absolutely nothing: in fact, the fusion takes places at around 32 degrees/second. But we have intentionally considered the motion to have constant velocity, which is exactly what does not happen: the motion is constantly accelerating.

We must now calculate the value of acceleration in order to capture the moment at which the hatchet 'disappears from sight' in a blur. Again, without reporting the calculation and, under the given geometrical condition, this point will be reached at $t = 0.04$ sec after the beginning of the motion. The hatchet's image travelled for only 1 degree across the retina, about 300 mi-

crons. In real space the model lowered his hand by only 52 mm! All the visual events taking place after this point are utterly invisible.

During the first 0.02 sec. the velocity of the hammer's image doubled from 6 deg/sec to 12 deg/sec. The value dv/v is defined by:

$$dv/v = v_2 - v_1/v_1$$

where v_1 is the initial velocity and v_2 the next one after the 0.02 second interval. For the first 0.02 sec $dv/v = 2$ while for the last time interval 0.14 sec to 0.16 sec the $dv/v = 0.15$. It is evident that the acceleration had slowed about 13-fold from the beginning to the end of the hammer's image course on the retina. A study by Notterman and Page in 1957 (Graham, 1965) shows an interesting relationship between the differential threshold ratio for the perception of accelerating movements and the initial velocity of the image. For an initial velocity of 6 deg/sec, which is our case, and with $dv/v = 2$ we are far above the threshold, which is only 0.17. This implies that if the initial velocity of the hammer image is $v_1 = 6$ deg/sec, we will barely perceive an acceleration if $v_2 = 7.02$ deg/sec. But when the image has attained the speed of $v_1 = 156$ deg/sec, near the end of its course and a final value of $v_2 = 180$ deg/sec we have $dv/v = 0.15$, which is enormously under the differential threshold. The acceleration will be utterly imperceptible.

It may be that this strict limit had filtered down the potentially infinite number of representations of similar actions, reducing them only to their initial states. Again, it must be remembered that this is no more than a simple exercise, the results of which may be added to a very long and complex series of other causes.

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CHAPTER 3

Continua in vision

Jan J. Koenderink

When Riemann (Riemann, 1854, *On the hypotheses that lie at the basis of geometry*) thought of examples of "multiply extended continua" he came up with (only) two: The "space of colors" and the "space we move in". The space of colors is of a purely optical nature. Although the space we move in occurs in optics, acoustics and haptics I merely consider the visual spaces here.

What is "vision"? Here I define "vision" as "*Optically guided potential action*". This definition is close to one common in biology, which reads "Optically guided action". The difference is a crucial one. The latter definition is manifestly an operational one, for "optical" is understood as "pertaining to electromagnetic radiation in the spectral region of the action spectra of biological pigments" (realm of physics and physiology) whereas "action" is overt, recordable behavior and "guided" is subject to empirical test (some variations in the optical domain are correlated with modulations of overt behavior). My definition differs from this through the shift to "potential action".

Potential action might seem an entity that doesn't have a scientific meaning and certainly cannot be operationally defined. Indeed, it has to be defined via a model in which one agent (the "scientist") studies another (the "subject"). The scientist is supposed to have (partial) control over the goals of the subject. If the subject is a monkey the scientist deprives it of water (say decreases body weight by ten percent) and then assumes that the monkey will cooperate for a droplet of juice. If the subject is a human the scientist arranges suitable payment to ensure cooperation. The scientist then records actions over a variety of tasks involving optical interaction and extracts the invariant core: The *potential* action. Here is a concrete example: Can the subject discriminate beams of radiation on the basis of spectral composition? In order to find out, the scientist presents pairs of beams that are either equal or different and varies the task such that the invariant core is knowledge of equality. Examples are: "Say equal when equal, unequal when unequal", "raise right hand when equal, left hand

when unequal", "kick floor two times when equal, three times when unequal", *etc.* When the subject passes all tests, the *actual* tasks must be irrelevant and I say that the equality or unequality of the beams influences the *potential* actions. This is "vision" as revealed by "psychophysics" in terms of my definition.

Notice that a mechanism that checks for possible obstacles between elevator doors has "vision" in the biological definition, but not in mine (such a mechanism has no potential action). Molluscs and possibly extragalactic aliens also (may) have vision in terms of the biological definition, but not in mine (the scientist has insufficient control over their goals). A certain degree of *empathy* between scientist and subject is required for psychophysics to be possible. Otherwise only physics and physiology remain and there can be no distinction between mere photoreactivity and vision. Whether you agree (with me) to rank psychophysics under the sciences or not is perhaps a matter of taste.

This definition is implicit in "folk psychology". When a public address system announces the arrival of a plane on an airport and one sees several people start move to the gate, one assumes that they both heard and understood. Yet the motor act of moving to a gate has little to do with hearing, nor with understanding a language. Moving to the gate reveals a potential action, the succession of public address and people moving to the gate (their number ruling out a chance occurrence) indicates that the actions were induced by the message. It is easy enough to think of circumstances in which the same message would likely have evoked different actions. The point of the definition is of course that perceptions are *mental* facts, rather than facts of physics or physiology. The biological definition tries to avoid this and consequently fails to distinguish between physiology and psychophysics.

For human vision in generic terrestrial environments, optics can be summarized in terms of the radiance field (Gershun, 1939). The radiance describes the spectral photon number flux density as a function of position, direction and time. It specifies anything that might be seen at any position, looking into any direction. The radiance provides a complete description of the physics. Human subjects only sample a tiny fraction of the radiance since they are only at one place at a time and sample only about a million (number of fibers in the optic nerve) directions at any one time. These "directions" have a fuzzyness, ranging from about a minute of arc (foveal vision) to a few degrees (far periphery of the visual field). Thus we can give a complete description of the "input part" for vision – at least in principle. Of course the current state of movement (often selfinduced by the observer) and body posture, as well as a large corpus of both accidental and generic facts concerning the environment and its causal nexus (laws of physics) are also part of the input.

The "space we move in" occurs as the two dimensional manifold of visual directions (the "visual field" say) and as the space of perspectives that we experience when we move with our eyes open (I will call it the "visual world"). These spaces occur to us as simultaneous–successive presences. Of course one never "sees" geometrical entities like points or lines. On the cognitive level one experiences objects and events, these may differ greatly in their degree of articulation. "Color" is understood as a quality of objects, though "color" is as much an abstraction as a "point". One cannot see color without seeing it as the color of something at some place and one cannot see a point without there being a colored object at it.

Geometry and colorimetry are fully objective. They describe physical correlates of the visual field as twodimensional, the visual world and color space as threedimensional continua. In all three cases one finds that the psychophysical structures that correspond to these objective manifolds are complicated and perhaps less constrained. The visual world changes as one moves through it or when it is occupied differently, the colors of a pile of colored chips change when you shuffle them. The existence of geometry or colorimetry in no way implies that one understands the psychophysical continua. Moreover, from anatomy and physiology one knowns that the visual field is served by more than a million degrees of freedom, but color space by only three (three types of cone action spectra). Thus the dimension of the spaces we move in and of colors (both three) are of a quite different nature. And even a million degrees of freedom implies only a finite set, definitely not a continuum. How should a "perceptual continuum" be defined? Of course I'm only interested in definitions that allow for psychophysical investigation.

What are "perceptual continua"?

There exist distinct mathematical notions of "continua". None appears to apply to the notion of "perceptual continuum" though. Some major considerations are:

- apparently perceptual continua are – physiologically – sustained through *finite* structures. (Psychophysics is unable to contribute on this point);
- the electrochemical changes in the brain that sustain perceptual phenomena have limited dynamic ranges and are subject to stochastic fluctuations, either due to the transduction (photon shot noise) or neuronal changes;

- the perceptual continua are bounded (they don't extend to infinity) and have finite levels of resolution (there is no "infinitesimal domain");
- perceptual continua fail a clearcut topological structure. The visual field may be a two-dimensional manifold at coarse levels, but spatial order becomes uncertain at fine levels;
- there exist limits to the complexity of configurations in perceptual spaces. Up to half a dozen sheep look like groups in particular geometrical configurations, but a few dozen sheep look like a "flock" which has a shape of its own and in which the positions of individual members are lost;
- various entities of a geometrical nature need not be dependent upon each other the way they are in geometry. For instance, a visual object may be seen to move, but not change location, something that would appear paradoxical in kinematics but is nothing special in psychophysics.

How then to define "perceptual continua"? The question invites a definition in the operational sense:

> *Two perceptual objects $\mathcal{F}$ and $\mathcal{P}$ (say), corresponding to physical stimuli Φ and Ψ (say) belong to a single perceptual continuum if one is able to construct a (finite) series of stimuli $\Xi_1, \ldots, \Xi_N$ (say) with $\Xi_1 = \Phi$ and $\Xi_N = \Psi$ such that two successive perceptual objects corresponding to this series of stimuli cannot be discriminated.*

In practice one may often construct such a series through interpolation. For instance, select some integer number N (say) and set $\Xi_i = \Phi + i(\Psi - \Phi)/N$. Thus these two points belong to a perceptual continuum:

. .

for when I construct this set of points:

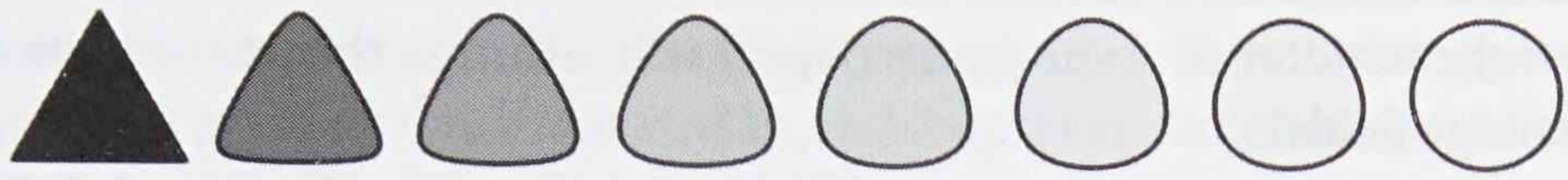
(I took $N = 800$) you cannot discriminate between a single point (like this: " . ") or a pair of successive points (like this: " . ").

These two graylevels likewise belong to a single continuum:

For here is a series that connects them:

You are unable to distinguish the graylevels of any two successive squares, yet you easily detect the distinctness of the original two graylevels.

Here is one other example:



Here the continuum is between black triangles and white circular disks (because I have to use monochrome I can't show the continuum between Wassily Kandinsky's red triangles and blue circles (Kandinsky, 1910)). Clearly, I could have taken an arbitrary combination of qualities, even a multimodal one.

How one constructs the series is irrelevant, there may be many ways to do this. For the sake of argument I have assumed that it can be empirically decided whether two stimuli are discriminable or not. "Discrimination" is a complicated concept though. When one sets up a two alternatives forced choice (2AFC) experiment in which same and different stimuli are randomly presented (with 50% probability) one finds that the probability of saying "different" rises from 50% (chance level) to 100% (dead sure) gradually when you steadily increase the difference from a low value. Some conventional criterion (say the 75% level) defines "the discrimination threshold". I see no way to remove such a conventional criterion from the definition.

This definition is workable and has great intuitive appeal. It avoids any judgments concerning the perceptual nature of the stimuli. This is good because such judgments as "both are colors" cannot easily be given scientific sense whereas a 2AFC procedure is flawless. However, I can think of many "perceptual continua" that would not readily occur to most people (they didn't to Bernard Riemann). For instance, the set of all human faces is a continuum for there is always someone that I will confuse with a given person. The co-occurrence of some tone and some color belong to a continuum, for I can (on my computer) construct colored patches and sounds that co-occur in a given space–time window and that interpolate between them. Although the latter example may appear a weird one, it becomes less troublesome when one experiences the interpolating set. The members are very similar except (perhaps) the two limits (a tone and the color of the background, a color and the noises of the background). I have no objections against such cases and accept the definition as a working one.

The definition given here is by no means the only possibility. For instance, one believes in the continued existence of things even though they change continually. The matter that makes up your body is different from what it was last year for instance. We all heard the story of the old woodcutter's axe, the one that served him all his life, though he had to fit a new handle five times

and a new blade twice. Thus one may have discrete instances that are experienced as a continuum. Something similar occurs with the scenery that passes behind the window of a railway carriage. I will return to this in the section on "homology fields".

Types of continua

The definition of "perceptual continua" leaves room for a variety of "implementations". The major dichotomy is that between *local sign* and *magnitude*. The difference can be illustrated through a simple example: Think of the speedometer of a car. The speed of a car is an unsigned number of dimension (momentaneous) distance covered per unit of time. On the old fashioned dashboard the "speedometer" has a watch-like face. A needle rotates such that the point moves over a scale from zero to (in cheap European cars) 150 km/h (say). Such a device can – by its very construction – only indicate one speed at a time. On modern dashboards the speedometer may be replaced with a LED bar. On such a device *at least in principle* not just one, but several of the LEDs might light up! (You should probably think of such a phenomenon as an error since cars do only one speed at the time.) Such a device is capable of simultaneously "indicating" as many speeds as it has LEDs. This device codes speed by *which* LED lights and has as many degrees of freedom as there are LEDs, whereas the former device is only able to indicate a single speed, though on a continuous scale (infinitely many values!). I will denote the LED -- type mechanisms as "local sign" systems, the classical needle – type devices as "indicator" systems.

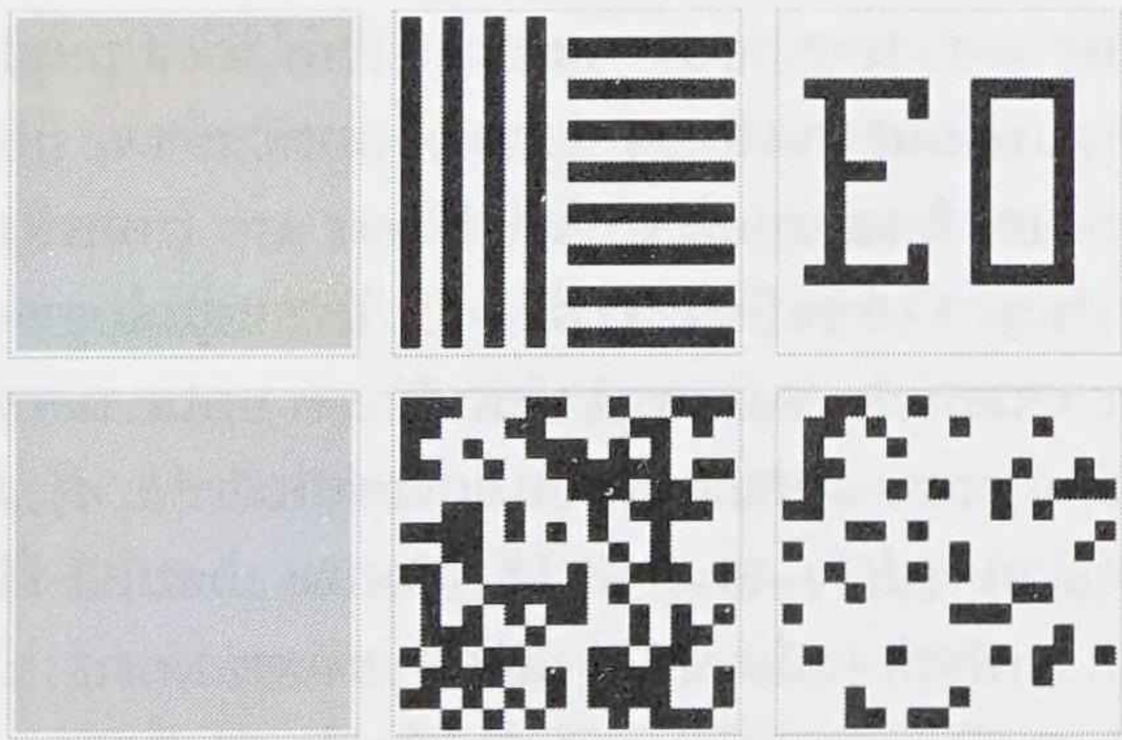
This dichotomy is fundamental. The visual field is of the local sign variety (two-dimensional, more than a million indicators) whereas color space is of the indicator variety (three-dimensional, only three indicators). The local sign systems were simply "understood" by anyone (although the concept of "local sign" was only framed by Lotze (1884) in the mid nineteenth century) whereas the indicator nature of color vision was only formulated (by Young, 1802) as late as the turn of the nineteenth century.

Lotze's local sign

Amblyopia often manifests itself in children at Kindergarten age. The visual acuity of one eye remains low, that of the "dominant eye" keeps increasing, and the kid tends to depend more and more on this dominant eye. When no

counter measures are taken the adult will become effectively monocular. The effective treatment is to *patch the dominant eye*, thus forcing the kid to depend on the retarded eye. The retarded eye then starts developing again and amblyopia is avoided. Once matured an amblyopic eye can no longer be cured.

Visual acuity is often measured with optotypes. Rows of characters are viewn from a distance. The ophthalmologist tries to determine the smallest height at which the characters can still be recognized. (With a truly amblyopic eye you can't read the headlines of a newspaper when the dominant eye can read the small print.) In the sixties another method to determine visual acuity became popular. One tries to determine at which "spatial frequency" a grating of sinewave modulated stripes can be discriminated from a uniform field of the same average luminance. Remarkably, one discovered (Hess, 1982) that for some amblyopes the dominant and the amblyopic eye were at a par on this task! This is most remarkable because it proves that both optically as well as neurophysiologically the amblyopic eye is not different from the dominant eye: Amblyopia is a *mental* deficiency. The type of amblyopia to which this applies is called "scrambled vision". Although the observer cannot read the headlines the observer can discriminate a textured from a uniform field but fails to make *sense* of the structure. It is as if the observer were confronted with a jigsaw puzzle and could clearly see all the pieces without being able to "do" the puzzle. One might say that the brain did not establish a proper topology for the amblyopic as it did for the dominant eye, the brain simply fails to discern where the optic nerve fibers of the amblyopic eye are from! Here is an example:



In the top row we have a uniform field on the left, and grating patterns with the same average luminance next to it. On the right we have two optotypes that should be easily discriminable from each other. In the bottom row these patterns have been scrambled. Notice that you can no longer discriminate the optotypes, in fact, you don't even see that there are two optotypes at all! Despite this loss of acuity you can still discrimate between the grating patterns

and the uniform field, in this respect your visual acuity hasn't suffered at all. (Of course you can no longer discriminate between the vertical and horizontal gratings any more.) This demonstration simulates the effects of "scrambled vision" quite realistically.

Lotze (1884) denied the possibility that the optic nerve comes (at birth) with an "address book". He also denied that the (then guessed, now certain) somatotopic mapping from the retina to the brain might solve the problem as most neurophysiologists today (at least implicitly) assume. That somatotopy cannot be the explanation is obvious. Consider the case of a brain operation where the surgeon puts the visual cortex into a knot. Will the visual field be knotted? Or suppose a (super-)surgeon permuted pyramydal cells in the visual cortex, keeping the wiring intact. Will this destroy the topology of the visual field? Of course not. The brain can't look at itself so it has no way to detect the operations, nervous activity would be unaffected. How does the brain know where the optic nerve fibers are from? Scrambled vision shows that the problem is not an academic one. Lotze's answer is that the addresses, or *local signs* have to be acquired through experience.

A mechanism that might serve to learn the local signs is due to Helmholtz (1896). Helmholtz noticed that people with toothache often are unable to indicate whether the bad tooth is in the upper or lower jaw. He explains this odd phenomenon (the condition can be excruciating) by noticing that in chewing food the nervefibers from the roots of the teeth are invariably excited in synchrony. He hypothesized that when the brain received input from two fibers that are always in synchrony it cannot but conclude that they are from the same position on the sensitive body surface. This idea might serve to explain how the brain can figure out the local signs of optic nerve fibers. It may use the correlation structure to determine which fibers are from (roughly) the same origin. This can be shown to suffice to deduce the topology of the visual field.

Here is a simple example. An organism has 6 optic nerve fibers $\{a, b, c, d, e, f\}$ and the following pairs appear to be correlated: $\{a, d\}$, $\{a, f\}$, $\{b, d\}$, $\{b, e\}$, $\{b, f\}$, $\{c, e\}$, $\{c, f\}$, $\{d, e\}$, $\{d, f\}$, and $\{e, f\}$. Notice that all fibers that correlate with a also correlate with d, indicating that a is *contained* in d, or $a \subset d$. Likewise we verify that $b \subset d$, $b \subset e$, $c \subset e$, $d \subset f$ and $e \subset f$. Since d contains both a and b, but no others, it may be said that d is the *connection* of a and b (hence d had better be called ab). Likewise e is the connection of b and c (a better name for e would be bc), whereas a and c are unconnected. Since a is connected to b and b to c it must be the case that b is *in between* a and c. The fiber f contains both connections and nothing more, thus the space is a *linear chain* $a \cdot b \cdot c$ (thus abc would have been a better name for f), we have figured out the topol-

ogy (Lotze's local sign) from the correlations (available to the brain, essentially summarized experience) using Helmholtz's principle.

Notice that, although we figured out that the structure is like $a \cdot b \cdot c$, it might equally well be $c \cdot b \cdot a$, in fact, you should not discriminate between these. But although these may be the same in terms of the brain as a machine, they are quite different when you consider the embedded agent in the world! In fact, the concept of an "agent" makes no sense if the world is ignored. The difference is similar to that of "above" and "below" in the visual field. Here Berkeley's discussion is to the point (Berkeley, 1709).

That Helmholtz's principle is very powerful can be seen from Huntington's proof that the overlap relations between circular discs (a simple model for visual receptive fields) generate the Euclidean plane (Huntington, 1913). In this model the radius of the discs may have a lower bound, thus the "points" are not necessarily small as many believe Euclid held. But remember that in Euclid's definition points "have no parts", their *size* is left out of the discussion. However, Huntington's construction cannot avoid the infinitesimal domain for you need circular disks with continuously distributed centers.

Here is another example of the generation of a local sign: Consider a conventional chess board (see Figure 1). Let receptive fields be defined as arbitrary rectangular areas, for instance the area $\mathcal{A}$ made up of the fields $\{B2, C2, B3, C3, B4, C4\}$. Suppose a "brain" possessed all possible receptive fields. When the single fields are independent (attached to nonoverlapping receptors on the sensitive body surface), two receptive fields are correlated when they share one or more individual fields. Thus the receptive field $\mathcal{B}$ defined as $\{B3, C3, D3\}$ overlaps with $\mathcal{A}$ because they share $B3$ and $C3$. I define inclusion and connection in the usual way. Consider the three points (smallest, or "atomic" receptive fields, i.e., receptive fields that contain no other fields) $B2$, $E4$ and $C5$. The points $B2$ and $E4$ are connected by the receptive field containing $\{B2, B3, B4, C2, C3, C4, D2, D3, D4, E2, E3, E4\}$. The three atoms define a "triangle". You easily check that the union of the "sides" of this triangle equals the connection of the three points (the "area inside the triangle"). Since the triangle is exhausted by the union of its sides, it is "empty". It is easy enough to show that *any* triangle is empty in this set! The conclusion has to be that the *dimension* of the space is less than two. Since the *sides* are not empty, the dimension is at least one. However, this one dimensional space is an odd one. For instance, the point $D3$ is on the side $B2$–$E4$. Yet, deleting the point from the side fails to divide it into two parts. Thus the sides are "thicker" than linear arrays of atoms. Clearly, Helmholtz's mechanism is able to generate some pretty weird spaces.

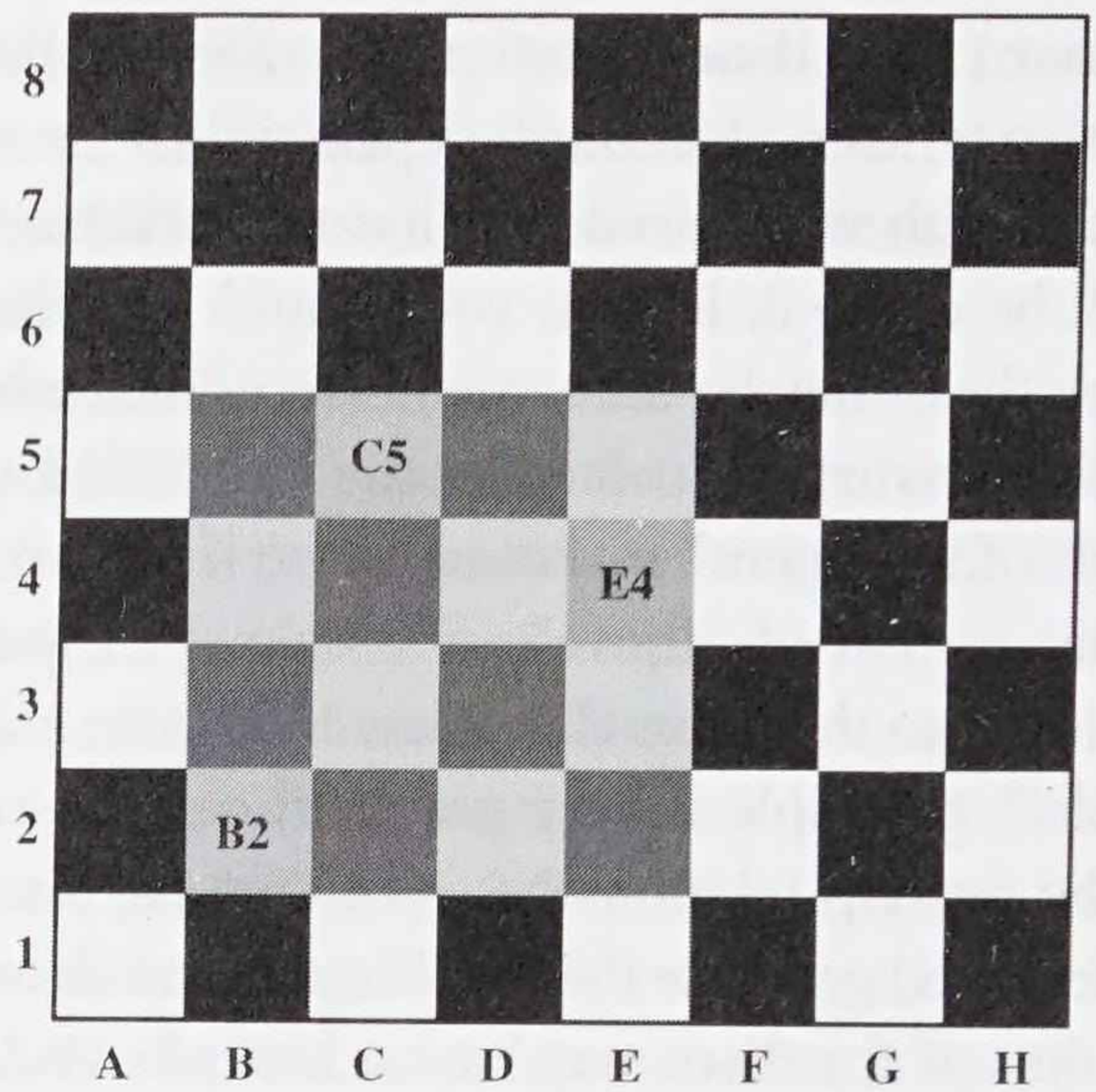


Figure 1. The chessboard example. The "triangle" defined by the vertices *B*2, *E*4 and *C*5 has been grayed out.

In order to arrive at a "nice" geometry (say a convex area as a model of the visual field) the receptive fields have to behave pretty much like the circular disks in the Huntington model. However, since the brain cannot "see" the receptive fields from the outside, one needs to give a fully functional definition of such an "ovate set" of receptive fields. This is possible though (Koenderink, 1984a, b), thus the brain is – in principle – in a position to generate the visual field on the basis of optic nerve input and check it for consistency.

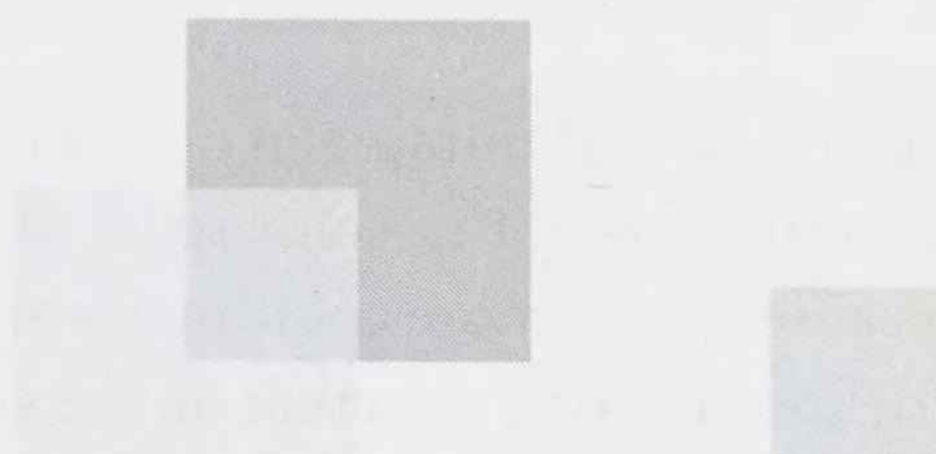
Indicator systems

Color vision is the key example of an "indicator system". It works much like a set of three speedometer devices attached to each location in the visual field. Thus there is no way to encode a sphere or a cube (both three-dimensional configurations) in color space at any single location of the visual field.

Notice that the effective stimulus for color is a spectral distribution of photon number flux density, that is to say, a density on a one-dimensional physical continuum. Of the infinitely-dimensional space of spectra only a three-dimensional subspace is discriminated, that is to say, any color (in the colorimetric sense) indicates an infinitely-dimensional (or "infinity minus three") space of beams, the so called "metamer" of the color.

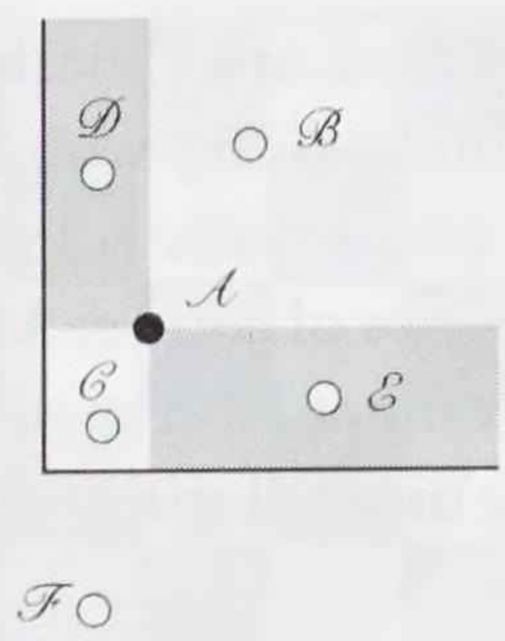
Color space doesn't need any "local sign", but merely that the three speedometers indicate monotonically with the amount of physical stimulation. Thus we are in a far less problematic situation than for the case of the visual field. This is bought at a price of course: A patch cannot be both red and blue at the same time, thus I cannot have spatial configurations in color space, at least not without drawing on "real space" (the visual field).

Even in cases like this:



the tiny square (the "overlap area" on the left) is only light and dark at the same time because of the *spatial* context. If you isolate it (the single square on the right), it is simply average gray.

Indicator systems may have complicated structures, depending on the coupling of the indicator to the physical substrate. For instance, in color vision one has three indications $\{L, M, S\}$ (standing for long, medium and short wavelength sensitive cone action spectra). One obvious constraint is that no indication can ever be negative (there is no "negative" radiation density). In actuality the constraints are even stricter because the action spectra overlap heavily. For the sake of simplicity I will assume that nonnegativity is the sole constraint though. The superposition (addition) of incoherent beams leads to simple addition of the indications ("Graßmann (1853)'s Laws"), thus superposition of beams A (indications $\{L_A, M_A, S_A\}$) and B (indications $\{L_B, M_B, S_B\}$) leads to indications $\{L_A + L_B, M_A + M_B, S_A + S_B\}$. This leads to a very special type of "conical order": I will say that "beam A dominates beam B" when it is the case that $L_A - L_B \geq 0$, $M_A - M_B \geq 0$, and $S_A - S_B \geq 0$. This simply means that there exists a beam C (say) that when superimposed on beam B yields beam A. Then each indication generates three sets: The set of all indications corresponding to beams it dominates, the set of all indications belonging to beams that dominate the fiducial one, and all other indications. The first set defines a finite volume in color space (the space of possible indications), the other sets infinite volumes. Here is an example:



The color $\mathcal{A}$ is dominated by $\mathcal{B}$ and dominates $\mathcal{C}$, whereas colors $\mathcal{D}$ and $\mathcal{E}$ are in the "other" set. The point $\mathcal{F}$ is not in color space at all since the system is unable to indicate it because one or more coordinates are negative.

The conical order defines a strong structure on the space that can take over the role of local sign. It defines a geometry that is very much like the chess board example discussed earlier.

Serial order

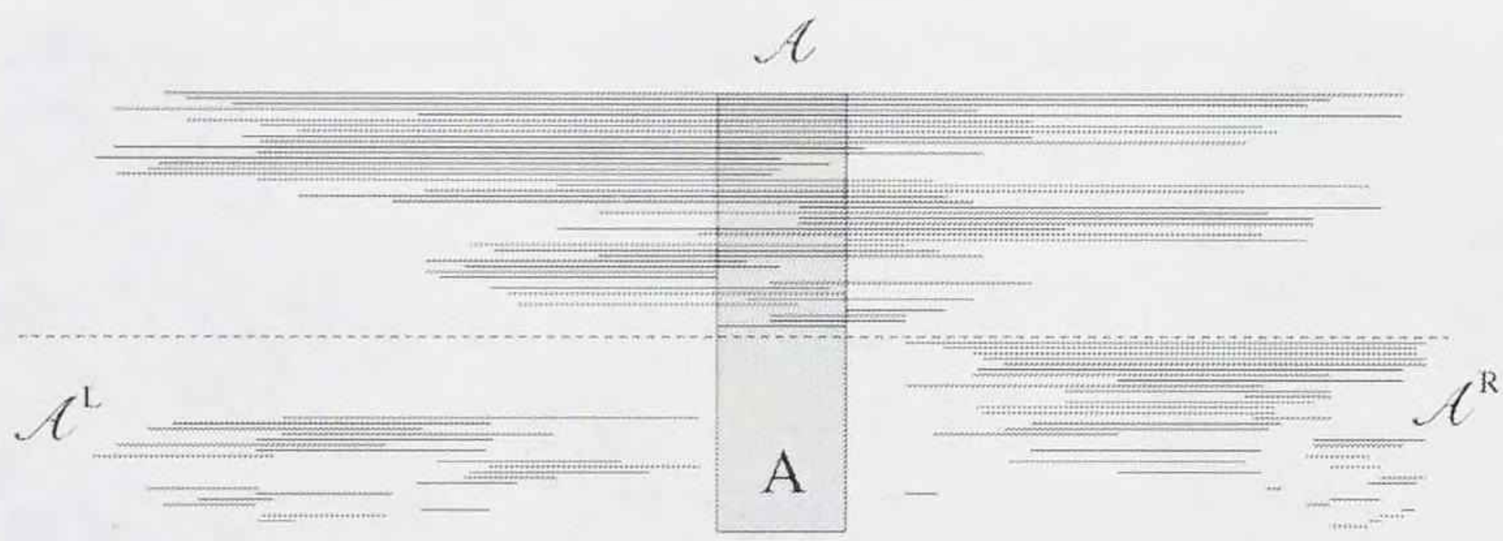
There exist many varieties of serial order in vision, perhaps the most pervasive being the temporal order. Collinear points, brightness, the hue circle, they also subtend serial orders, but come embedded in higher dimensional spaces. Here I will use the language of temporal order, many observations apply equally to the other instances.

The experiences that sustain temporal order may be called "threads". Threads have internal structure, though not necessarily a serial order themselves. One may think of short cuts from a movie, disregarding precise order. Threads may overlap in the sense that they may contain the same event (next to other events). For instance, in driving to work one thread might be a pedestrian crossing, another one my adjusting the rear view mirror. These threads might overlap, yet are distinct experiences in the sense that I might be able to remember each, but not necessarily their temporal order.

In a very simple model one assumes that the threads may contain a finite number of elementary events. In a thread, the events have no order (at least, I will disregard it), but are like marbles in a bag. From a metaperspective we know that the threads contain contiguous cuts from the linearly ordered sequence of events. In order to make this more concrete, think of a long, continuous movie sequence (no scene cuts). We make many copies of the movie and

cut all of them into shorter or longer pieces. Each piece we cut into individual frames and we put these frames in a bag (shuffled of course). Thus we end up with a large pile of such bags, all bags unlabelled, these are models for the threads of experience. One wonders whether this underlying order is implicit in the threads of experience, can one reconstruct the movie sequence from the pile of bags?

The reasoning can be as follows: When it is the case that whenever thread A overlaps with thread P, then that thread P also overlaps with a certain thread B, then we say that "thread A is contained in thread B". When thread A doesn't contain any other threads I call it an *atomic* thread. Pick any atomic thread A (say), then I divide all other threads into three classes: The class $\mathcal{A}$ of all threads that overlap with A, and two classes $\mathcal{A}^L$ and $\mathcal{A}^R$ such that no element from $\mathcal{A}^L$ overlaps with elements of $\mathcal{A}^R$ (and *vice versa*). The latter two classes may be called the "threads to the left" and "to the right" of the specious moment $\mathcal{A}$ defined by the atom A (all threads overlapping with it). The triple $\{\mathcal{A}, \mathcal{A}^L, \mathcal{A}^R\}$ is an embedded "moment". Here is an example:



The specious moment extends far beyond the atomic thread proper. The left and right sets are divided by the width of the atomic thread. The moments admit of a natural linear order, for any atomic thread overlaps either with members of the set to the left or members of the set on the right of any other atomic thread. Even though the atomic threads are linearly ordered, they may (heavily) overlap. In this way one obtains a model of the perceptual continuum: The specious moments change little from atomic thread to atomic thread (like the woodcutter's axe discussed earlier), they "propagate identity" between the disjunct atomic sets.

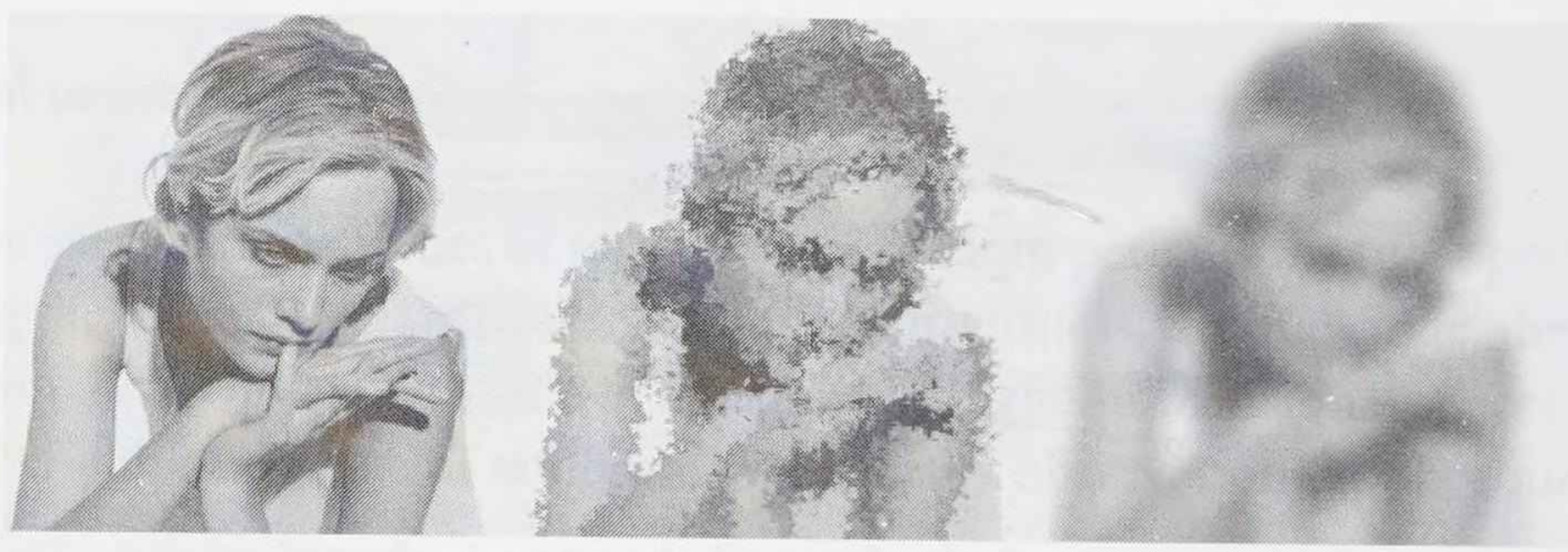
Locally disorderly systems

Even the normal visual observer is severely handicapped in the sense that many simultaneous orders lead to "texture", rather than spatial configuration in the

true sense. An example is "foliage". Although you discriminate oak from beach at a glance, it is not the case that you perceive all leaves individually (Ruskin, 1873). You don't know their number for instance. You may change one spatial configuration of leaves for a totally different one and never notice a change of "foliage". Textures apparently are a type of "summary descriptions". In everyday perception textures are ubiquitous.

At the highest resolution in the fovea and even at moderate resolutions in the peripheral visual field, one sees texture rather than pattern. That is to say, one sees details without necessarily fitting these in a well determined simultaneous order. It is much like a mild case of "scrambled visual field", I will speak of "locally disorderly" perceptions. With "disorderly" I mean that no order exists, rather than any specific nonveridical order. It is a bit like the visual field were rendered in a "painterly manner". The true painter does "foliage", rather than "leaves". The brushstrokes indicate "leafiness", but there is no attempt to paint leaves (Homer, 1964).

Here is an illustration:



Notice that the original picture (left) loses much detail when the local disorder occurs at easily discernable scales (middle). Yet such a rendering looks much "better" (painterly maybe?) than a blurred version (right), even though the amount of spatial detail that can be made out is quite similar. The locally disorderly rendering has retained the histogram of graytones whereas the blurred one has not, thus it indeed does preserve more information (though not spatial detail) than the blurred rendering. It also looks more "reasonable" though, in the sense that the blurred picture makes you doubt your acuity (wrong spectacles?), the locally disorderly not, it looks sharp! Local disorder generates perceptual continua in that it makes slightly different physical scenes indiscriminable (Koenderink and van Doorn, 1999).

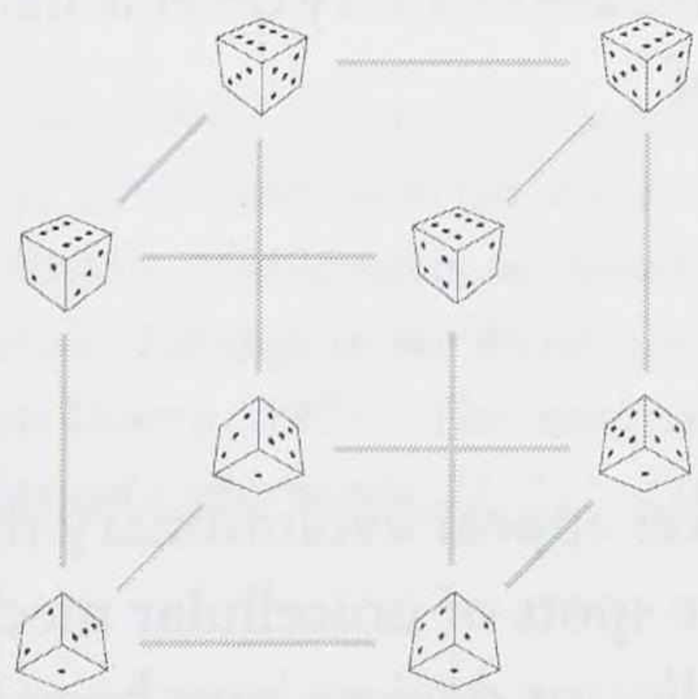
More technically, it seems that the visual field breaks down at high resolution. Details are resolved, but there is no topological structure. The situation is much like with the threads I considered in the section on serial order.

The threads are articulated entities but have no internal serial order. At the subatomic level the serial order gives way to disorder.

Homology fields

Apart from local sign and indicator mechanisms there is a third mechanism that generates perceptual continua and that seems to be present throughout the animal kingdom. It might be described as "family likeness", I will use the biological term "homology field". Although cars of the various makes are different (the manufacturer tries to make them look distinguished), they are also all very similar (Thompson, 1961; Riedl, 1997). I can place them in a "homology field" and easily interpolate between a sedan and a station wagon (say). Such a homology field may even contain diligences (the fact that most cars have the engine in front clearly derives from the horse in front of these carriages) and railway locomotives. Likewise, we immediately perceive the family resemblance of people, cattle and dogs. These are no doubt continua, even in view of the fact that we never saw an animal in the space between cattle and people, we can clearly conceive of a minotaurus say.

The visual world (Poincaré, 1902) is like this, it is a "space of perspectives". Consider any object, say a cube. It is a basic fact of (optical) life that you can see only the front of opaque, radiation scattering objects (human bodies, rocks, trees). Thus you can see not more than three faces of a cube simultaneously. A perspective may reveal one, two or three faces, although the triple face views are by far the most frequent. For the sake of conciseness I will disregard the single and double face perspectives here. There are certain regularities in the transitions between qualitatively different perspectives, this is most conveniently summarized in the form of a transition graph (Koenderink and van Doorn, 1979):



Notice that successive views share the view of a pair of faces. When you remain within a single three-face view, the perspective still changes quantitatively:

The aspects under such changes subtend an approximately two-dimensional homology field. Thus the perpectives of the cube can be ordered as a number of homology fields between which certain transitions are possible. Of course the aspects are bound to the shape of the object as well as the relative position of the vantage point.

Each object, or configuration of objects, even whole scenes, yields such bundles of homology fields (Gibson, 1979). The "visual world" is like a huge atlas of such entities. Apart from perspective, you may also construct homology fields for the various "renderings" of the objects, say the changes under shifts of the dominant light source.

There is little doubt that learning to see means to develop the ability to deal with such homology fields. These are the most articulated perceptual continua and at present one lacks the formal tools to handle them properly. Relevant psychophysics seems to be lacking altogether.

Conclusion

Perceptual continua in vision are of a very diverse nature. Yet all of them appear to fit into the trichotomy of

- indicator devices,
- local sign systems,
- homology fields.

Of these the *indicator devices* appear evolutionary the oldest. The simplest examples in vision are the eye spots of unicellular mechanisms. In higher organisms more complicated indicator devices have been formed, like the opponent

color channels in primates, the cortical simple cells (they indicate degree of edginess or barness), and so forth.

Local sign involves the topology of visual fields. In principle one may envisage mechanisms that show angular resolution (also in their overt behavior) but lack proper local sign. Such mechanisms would have "blindsight", essentially a form of reflexive behavior. When angular articulation drives potential behavior one must have local sign and the visual field must be a mental entity, not just a pattern of physiological activity driven by optical stimulation. Thus local sign must be established ontogenetically (in humans apparently during the first decade of life), although the potentiality to develop local sign is no doubt of phylogenetic origin. One believes to detect local sign with most vertebrates, perhaps even insects.

Homology fields are the most complicated and structured continua. Primates appear to almost automatically fit optical structure into such homology fields (as when you see faces in clouds). For some homology fields (faces, perhaps body posture, generic body motions) specific brain centers have been found in primates (Zeki, 1993). In such cases one perhaps has transitions to spaces defined by indicator devices of very specific type. In most cases one cannot point out the neural substrates for homology fields though.

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CHAPTER 4

Visual forms in space–time[1]

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1. Motivating problem

Vision is, above all else, a system for acquiring information about the spatiotemporal structure of the environment – for recognizing and locating objects, for knowing where one is and where one is going relative to surrounding objects and events, and generally for appreciating the structure of one's surroundings.

The effectiveness of vision in acquiring spatial information is wonderful, both scientifically and esthetically. Indeed, it is so effective that usually we are not even aware of the process of seeing as such – as an active and purposeful process, with limitations, requiring time, and subject to errors and failures. Training in science or art usually is required for having much thought about the mechanisms and processes of spatial vision.

Ironically, despite the importance of spatial vision in biological functions and in consciousness, contemporary science is still rather vague about how the visual system represents the spatial structure of stimulation, let alone how it represents the spatial structure of the outside world. General agreement does not yet exist about even the definition of the problem.

Two competing conceptions of spatial vision involve different descriptions of optical information and different strategies for understanding how this information is used by visual mechanisms. For simplicity, we can label these the "local energy" and "field theory" approaches. These two approaches stem from contrasting intellectual traditions and strategies. The former seeks explanation in terms of smaller-scale component parts and processes, whereas the latter seeks understanding in terms of the dynamics of larger-scale systems. These

two strategies need not be mutually exclusive, but they generate different issues and usually different conceptions of perception.

The local energy approach begins with the description of stimulus patterns as local shots of energy and then asks how these are visually assembled into meaningful units. Anatomical and physiological findings guide theories about how signals from the photoreceptors are grouped and encoded in neural networks. The array of photoreceptors usually serves as the reference frame for representing spatial patterns. Environmental spatial relations cannot be directly represented by reference to these anatomical coordinates, however, so an homunculus generally is needed implicitly for recognizing and interpreting neurally encoded information about space. This elementalist approach is compatible with structuralism, empiricism, and behaviorism, but leads to riddles about the neural representation and perception of spatial organization and meaning.

The field theoretic approach aims instead to characterize information as patterns rather than stimulation as energy. It begins with the question, What environmental structures and changes are meaningful to the behaving animal? If information is based on optical properties important for the function and survival of the animal, then the nasty problem of the meaning of stimulation is solved in principle and handed to ethology for details. Spatiotemporal stimulus patterns are described differently than in the local energy approach – structured by the environment rather than by the animal's sensory organs. The question of exactly how these spatiotemporal patterns are neurally represented and detected often remains unanswered, however.

The Gestalt theorists adoped this field theoretic approach late in the 19th century. They studied stimulus patterns with readily perceivable global organization, and they sought principles of brain organization that might explain such perceptual organization. The explanatory mechanisms were not found, however, and this failure was chiefly responsible for the demise of the Gestalt approach. The Gestalt approach was compatible with wholism, functionalism, nativism, and rationalism, but did not clarify the mechanisms of spatial vision and perception. Recent progress in describing optical information, however, suggests new ideas about visual mechanisms for organizing spatiotemporal fields.

The present paper examines the spatiotemporal structure of information for vision. We will describe first some basic theoretical problems of spatial vision and then some key research results concerning the perception of structure in moving optical patterns. The concept of *information* is important in this discussion. Basic issues concern how information is contained, first, in the struc-

ture of visual stimulation and, second, in the structure of neuronal responses to that stimulation. Our aims are to show how the spatiotemporal structure of optical stimulation constitutes visually effective information for perceiving the spatial structure of objects, and to suggest visual mechanisms for acquiring and using this information.

2. Some basic problems of spatial vision

Basic theoretical problems in the study of spatial vision concern (a) the spatial correspondence between environmental objects and their retinal images and (b) how the spatial structure of retinal images is represented by the visual nervous system. Four such basic problems are the following:

1. *Space*

The projective map from 3D environmental space to 2D retinal image space entails a loss of dimensionality. Environmental objects and events are positioned and shaped in 3D space and are experienced in 3D spaces, but the retinal stimulation has just two spatial dimensions. The binocular system, with two redundant but spatially separate arrays of photoreceptors, provides some intrinsic 3D spatial information through stereopsis, but stereopsis alone is insufficient to explain the effectiveness of vision for 3D spatial relations. The simple fact is that neither relative distances between points, nor relative directions between lines, nor even collinearity nor bilateral symmetry are preserved in the projective map from environmental surfaces onto the eye. How, then, can the spatial structure of retinal images provide information about the spatial structure of the environment?

2. *Motion*

The spatial form of optical stimulation is continually changing. Objects move and observers move, altering both the spatial form and the scale of optical images of even rigid solid objects. According to some classical conceptions of vision, image motion could only be a source of error in representing the spatial structure of stimulation; but several different lines of psychophysical research over the past 50 years have found repeatedly that vision is highly sensitive not only to image motions but also to the spatial structure of what is moving. Thus, motion seems to constitute a basic format of information about space. Nevertheless, the task of describing this changing image structure so as to reveal the stable spatial structure of the environment is not straight-forward. Many currently available ideas about the visual mechanisms for representing

image motion do not make transparent the stable spatial structure of moving environmental objects.

3. *Form*

Unified forms and objects are not readily identifiable parts of the spatial continuum of retinal images. Visually perceived forms are organized over a wide range of spatial scales in uncountably many geometric forms with varying degrees of connectedness. Solid objects in the environment usually are only partially revealed in the image – due to the occlusion of farther parts and objects by nearer parts and objects – and these occlusion boundaries change as the observer and objects move. Additionally, the image patterns of light and dark and color vary widely for a given object, depending on (a) the intensity, 3D directional distribution, and wavelength spectrum of the illumination, (b) the 3D orientations of the object surfaces relative to both the illumination and the observer, (c) the relative positions of other objects that cast shadows and reflections, and (d) the particular material properties of the objects that transmit, absorb, reflect, and scatter light. For these and other reasons, the problems of grouping local image features into globally connected objects and of segregating neighboring features as disconnected parts of different objects are far more challenging than one might first imagine. The subjective ease with which we see objects as clear and stable forms contrasts with their seeming ambiguities in the spatial continuum of optical stimulation.

4. *Multiple scales*

All three of the preceding problems involve additional questions about the spatial scales for describing both optical information and visual mechanisms that acquire and use this information: How is the global connectedness of environmental objects and events specified by visually measureable local properties of the retinal images? How is the global spatiotemporal structure of the optical images represented by responses of discrete local visual receptors and nerve cells? How are spatial connections, distances, and directions within and among objects represented by neural mechanisms whose anatomical structure is independent of the optical stimulation? How are macroscopic spatial organizations assembled from microscopic cellular and molecular components?

Problems in understanding the relations between local and global optical properties and between micro- and macroscopic visual mechanisms have persisted throughout the history of the philosophy, arts, and sciences of vision. These are persistent problems partly because the effectiveness of vision leaves them transparent to everyday experience, partly because they are subtle and difficult, and also because they are resistant to scientific reductionism.

These theoretical problems are not independent of one another. Specifically, motion may be a basic format for visual information. The coherence of moving images may be a basis for the perceptual stability of environmental objects whose retinal images are changing, for the visual organization of connected and disconnected objects, and for the 3D spatial structure of environmental objects.

3. Gestalt theory and research on 2D motion perception

Scientific reductionism seeks to characterize systems by identifying their structural elements and then describing the causal interactions among these elements and their compounds. The power of this research strategy has been demonstrated repeatedly throughout the past three centuries of science. Reductionism is exemplified in sensory physiology by Müller's doctrine of specific nerve energies and the concept of receptive fields, and in psychology by structuralism and feature-analytic approaches to perception.

Despite its successes, reductionism has been inadequate for dealing with the perception of *spatial* relations and forms. Beginning in the late 19th century, the Gestalt psychologists argued that an entirely different approach is needed for understanding the perception of spatial forms (Ash, 1998).

One phenomenon that motivated Gestalt thinking was the "phi phenomenon" of apparent motion – where a compelling perception of continuity in space-time is generated by the sequential presentation of two or more visibly discrete stimuli at neighboring spatial and temporal positions. Wertheimer (1912) emphasized the Gestalt character of this phenomenon – that a unified *relationship* in space-time is perceived which is not inherent in the elementary stimuli, and that the properties of the individual component stimuli often seem introspectively inaccessible. The qualitative property of motion and the quantitative properties of direction and velocity are *emergent* properties not defined by the components. Indeed, the spatial and temporal separations may be less accurately discriminated than the speed of motion (Lappin, Bell, Harm, & Kottas, 1975), as shown in Figure 1..

A related phenomenon discovered by the Gestalt researchers involved the grouping principle called "common fate". If a random or camouflaged set of features moves simultaneously with the same speed and direction, then the spatial relations among these elements are immediately perceived. Such coherently moving groups are perceptually segregated from backgrounds that are either stationary, moving in a different direction, or moving incoherently.

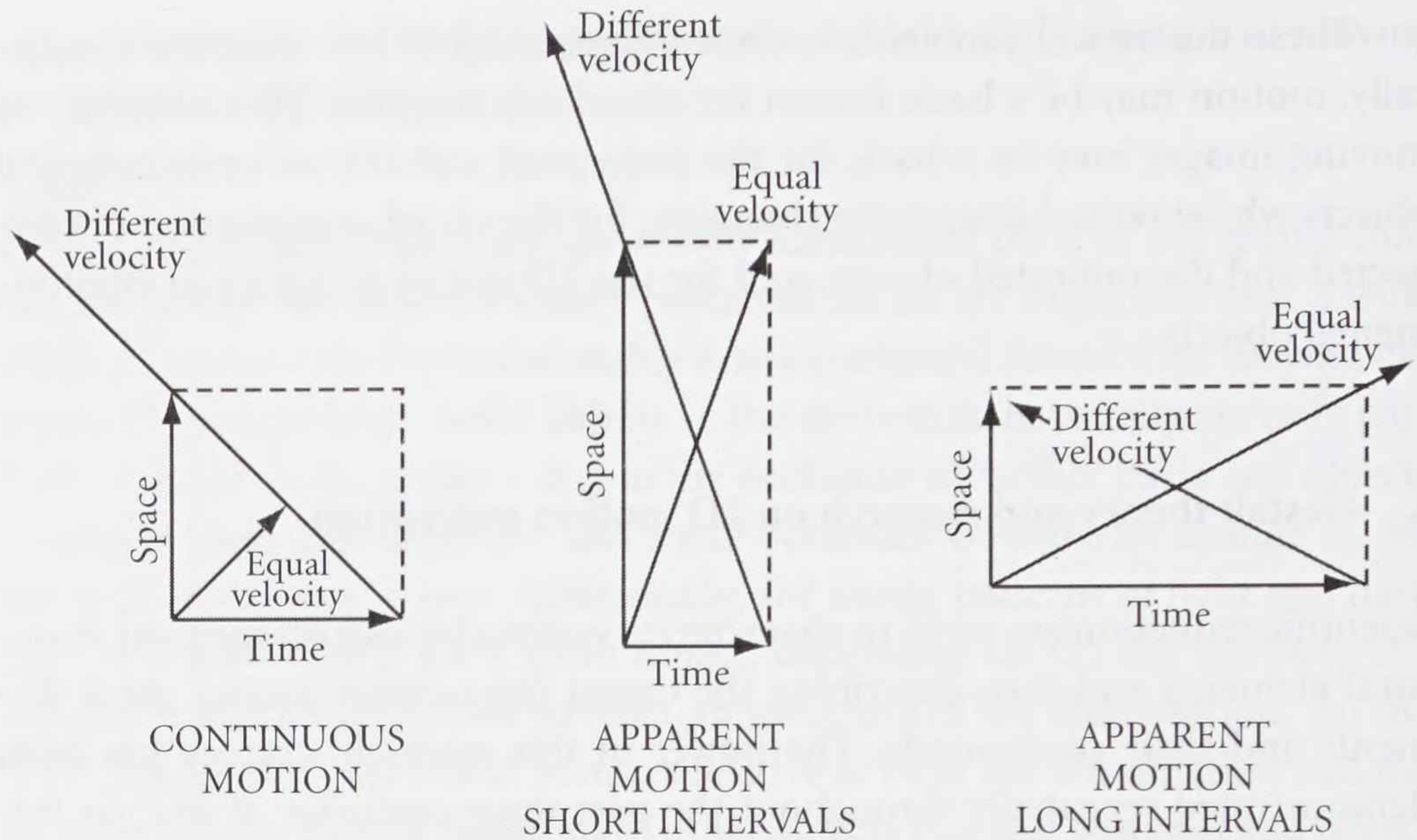

Figure 1. The relative discriminabilities of four different pairs of moving stimuli differing in either spatial extent, temporal duration, velocity, or both spatial and temporal extent with equal velocity. The relative discriminabilities of these four pairs are represented by the relative lengths of vectors. The discriminabilities of the stimulus pairs differing in only space or only time are given by the vector lengths in the vertical and horizontal directions, respectively; and the discriminabilities of the multi-dimensional stimulus pairs are given by the lengths of the diagonal vectors. If the spatial and temporal components were visually independent, the predicted discriminations of the multi-dimensional pairs would correspond to the diagonal distances in the rectangular diagrams. For both continuous motion and for apparent motion between lights separated by short temporal intervals (50 msec and 65 msec), the different-velocity pairs were discriminated more accurately than predictable from the independent discriminabilities of the spatial and temporal differences. (From *Journal of Experimental Psychology: Human Perception and Performance, 1*, p. 393, J.S. Lappin, H.H. Bell, O.J. Harm, & B.L. Kottas, Copyright 1975, American Psychological Association)

The commonality of motion is directly visible; and it enables the perception of spatial form.

Moreover, because the array of image points now extends in two spatial dimensions as well as in time, the changing spatial structure of moving forms entails several new emergent properties that do not exist in the space-time trajectory of a single moving point.

The importance of these phenomena can hardly be exaggerated. The set of phenomena related to common fate, involving the emergence of visually

structured spatial fields from moving patterns, has now grown very large. The relevant literature is still expanding, encompassing several different lines of theoretical and experimental research. The roots of this literature in Gestalt psychology sometimes are forgotten or unrecognized, but this body of reseach constitutes the principal modern progeny of Gestalt psychology.

The following list of experimental phenomena and theoretical ideas indicates a few highlights in this large tapestry of work:

Perceptual grouping by common motion

Spatial features that share the same motion are perceptually grouped and segregated from other features that are stationary or move differently (e.g., Anstis, 1970; Julesz, 1971; Bell & Lappin, 1973; Braddick, 1974; Lappin & Bell, 1976; Chang & Julesz, 1983; van de Grind, van Doorn, & Koenderink, 1983; van Doorn, Koenderink, & van de Grind, 1985). The common motion is immediately detectable even when composed of many hundreds of randomly arranged elements presented in just two frames each of only a few hundredths of a second. The unified perceptual organization of these patterns is suggested by the fact that its visibility *increases* with the number of component elements – approximately as the square root of the number of elements, corresponding to statistical additivity (Lappin & Bell, 1976). If the moving elements were individually reported to the higher neural centers of visual consciousness, then one might expect the perceptual capacity for such image data to be limited by the number of moving elements. But such limits are not found. Instead, the common motion vector seems to be detected directly at the initial stages of vision. Increasing the number of elements with a common motion produces visual fields that are visually simpler, more coherent.

A schematic illustration of such a multi-element vector field is shown in Figure 2.

Sensitivity to spatiotemporal coherence in noise

The visual sensitivity to the coherence of moving patterns is impressive and may be quantified by the smallest detectable portion of a dense random-element pattern that moves coherently. Such a coherence-detection threshold can be measured in several different ways – (a) by the ratio of coherently moving to randomly moving elements (e.g., Lappin & Kottas, 1981), (b) by the statistical distribution of motion directions (Williams & Sekuler, 1984) or (c) by the ratio of coherently displaced to randomly changed luminous contrast

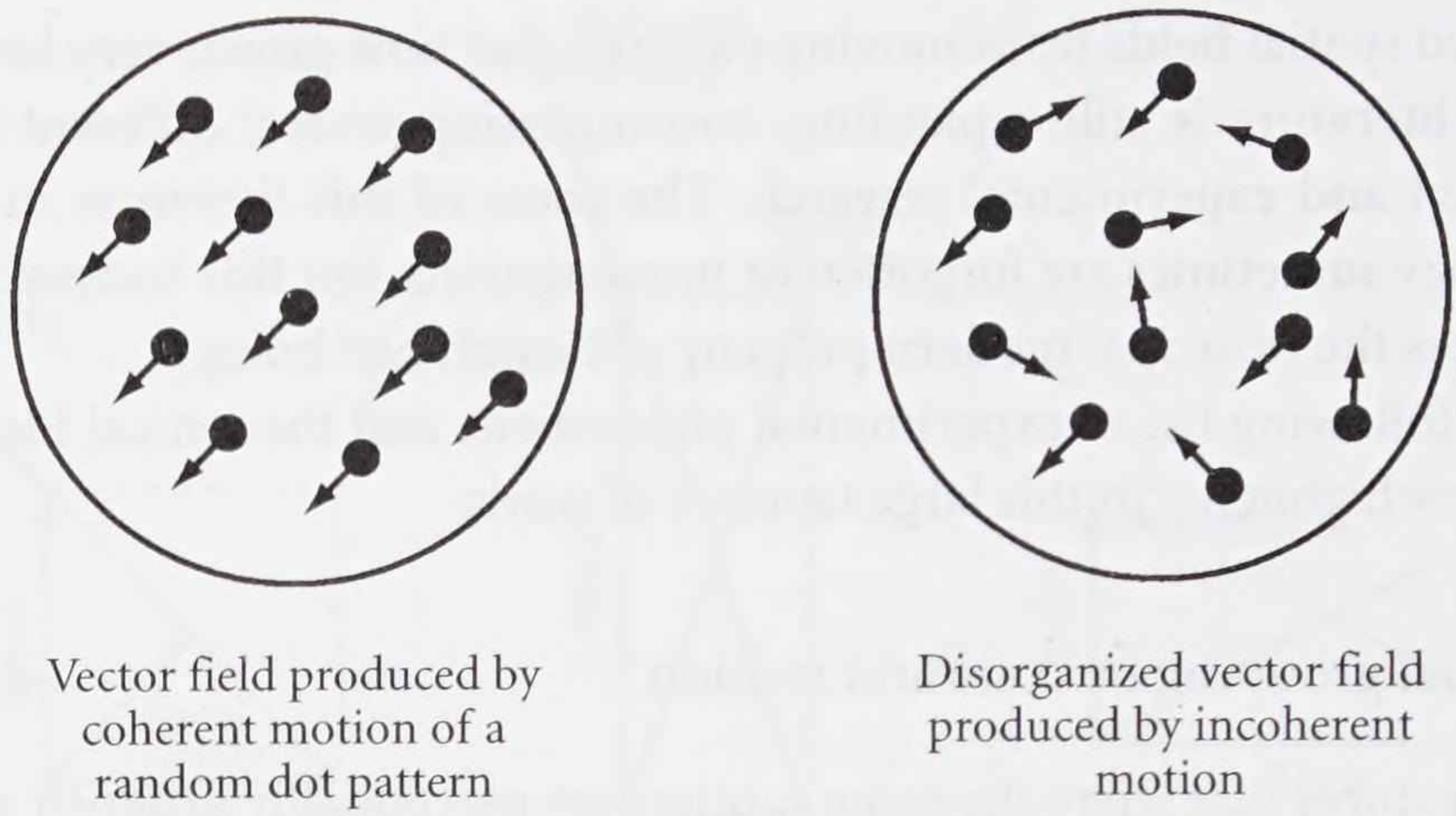

Figure 2. A schematic illustration of a spatiotemporal vector field produced by the common fate of multiple points simultaneously displaced in the same direction and distance. (We are grateful to Randolph Blake for this illustration.)

in a random-element lattice (e.g., van Doorn & Koenderink, 1982a, 1982b). The last of these methods is particularly interesting, because the component elements are invisible when stationary and are not even spatially distinct elements with stable edges, but are only portions of otherwise random luminances at each spatial and temporal position. Such coherence-detection thresholds are a small percentage of the whole pattern, often 10% or less (e.g., van Doorn, Koenderink, & van de Grind, 1985). Such phenomena suggest that vision performs a type of cross-correlation between patterns of stimulation at different positions in space-time, detecting components by the transformation parameters that characterize their coherent relationship.

Spatial and temporal limits

The perception of common fate might seem at first but a multi-element version of the phi phenomenon. Despite their obvious perceptual similarities, phi motion and common fate have qualitatively different spatial and temporal characteristics. The detectability of common motion in dense random-element patterns declines sharply with increases in either the spatial or temporal separation between successive frames, and these two factors have independent additive effects (Lappin & Bell, 1976). The subjective quality of phi motion, however, is best at spatial and temporal separations that exceed those for detecting coherent motion in dense random-element patterns. Because the detection of common motion in dense patterns usually is limited to small spatial displace-

ments, this sometimes has been called "short-range" motion, attributed to a limited span of local motion-sensitive mechanisms (Braddick, 1974). Research has shown, however, that the spatial displacement limit for perceiving common motion depends on the spatial size and statistical coherence of the moving elements rather than on the span of visual mechanisms (Bell & Lappin, 1973; Lappin & Bell, 1976; Chang & Julesz, 1983; van de Grind, Koenderink, & van Doorn, 1992).

Consider a set of commonly moving but spatially separate elements embedded in a background of randomly changing noise elements. The visibility of these moving elements must involve some type of spatial integration, and one expects that this integration must be limited by the spatial separation of the elements. The influence of this limit on spatial integration was studied recently by van der Smagt and van de Grind (1999). They found that the detectability of such moving structure declined rapidly with spatial separation. Moreover, detection was better for sets of target elements with the same contrast (all dark or all bright) than for mixed sets of both dark and bright signal elements. They concluded that spatial integration occurs in two stages – an intial contrast-sign-specific pooling within areas of limited spatial size, followed by a second stage with inhibitory interactions between the separate contrast-specific mechanisms.

Another striking organizational segregation was found for patterns moving at relatively slow vs fast speeds (van der Smagt, Verstraten, & van de Grind, 1999). The two different ranges of image velocity seem to be detected by separate and independent mechanisms, because they produce simultaneous transparent perceptions of both fast and slow patterns. Such transparency was found when the two moving patterns were spatially superimposed, when their aftereffects were superimposed, and when they were binocularly superimposed. These two different speed-sensitive mechanisms probably serve different visual functions. The slower-speed channel may be more responsible for perceiving spatial structure from motion, and perhaps the faster channel is more important in visually guiding locomotion.

Visual vector analysis of common and relative motions

Beginning with a now-classic doctoral thesis, Gunnar Johansson (1950/1994) demonstrated that the visual organization of moving patterns generalizes well beyond the grouping of elements with the same translations. The visual organization also includes *relative* motions – defined in relation to the common motion of a larger group of elements. That is, the direction and velocity of a

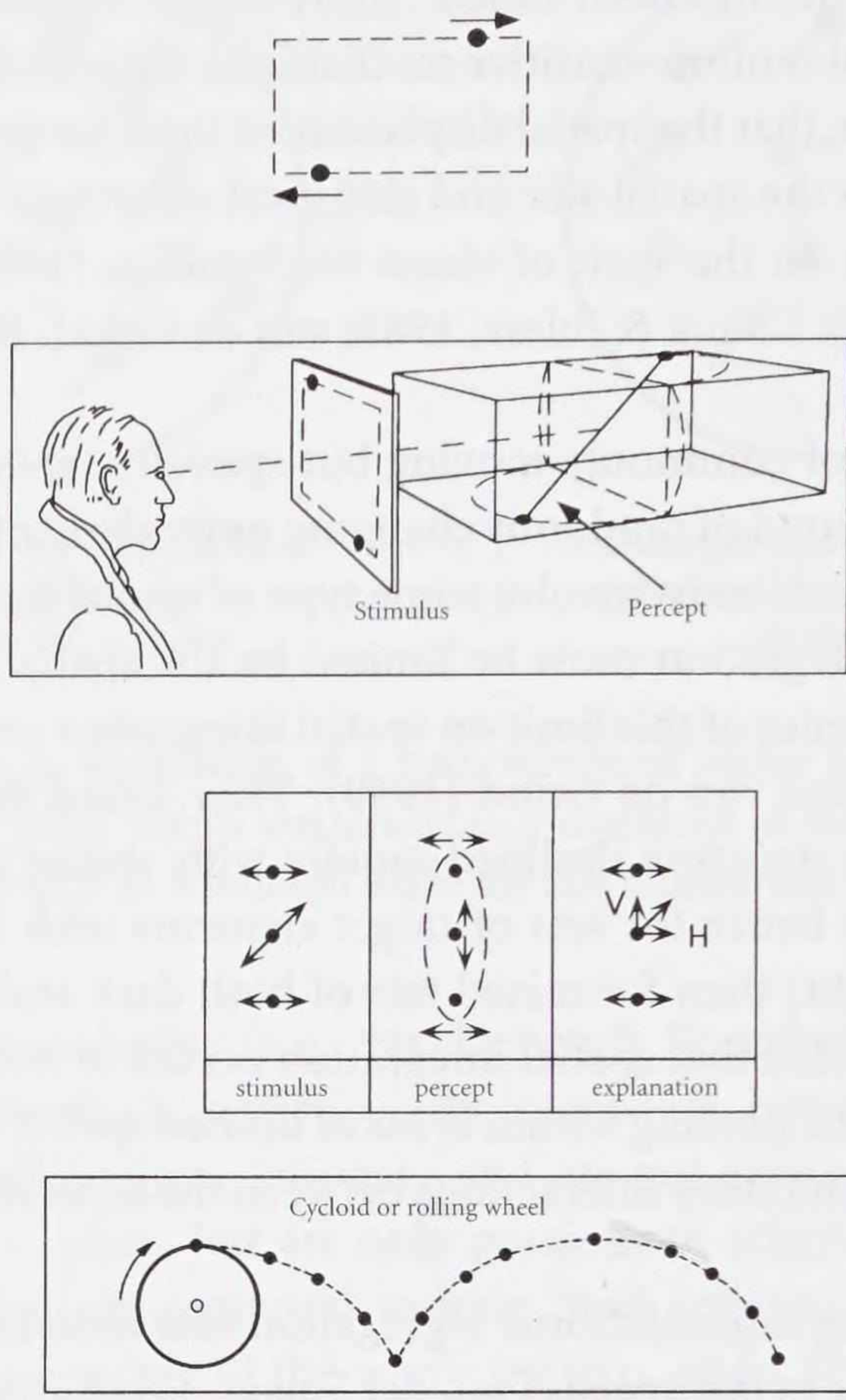

Figure 3. Schematic illustrations of the perceptual organization of simple visual patterns in terms of their common and relative motion components. The spatial frame of reference for perceiving these motions is not the rectilinear screen on which the individual points are displayed. Instead, the individual points are seen as connected and their motions are perceived in relation to that of a unified object formed by the other moving points. **Top:** Two points translating in opposite directions on opposite sides of an imaginary rectangle are perceived as the ends of a single connected rod tilting and slanting in 3D space. Thus, the space of the motions is visually defined by the perceived form that is moving within the space. **Middle:** A diagonally moving point is perceived as moving vertically within a horizontally moving framework defined by horizontally moving points above and below the central point. Apparently, the diagonal motion on the screen is visually analyzed in terms of its horizontal (common) and vertical (relative) components motions. **Bottom:** When a central reference point with the same horizontal motion is added to a display of a cycloidally moving point, the cycloidal motion is no longer visible. The cycloidal trajectory is perceived instead as a simple rotational motion, as on the rim of a rolling wheel. (Adapted from Johansson, 1975, with permission of the artist, Alan Iselin.)

given dot can be visually altered by a moving frame of reference provided by the neighboring optical pattern. The pattern as a whole becomes a reference frame for visually defining the directions and speeds of the component elements. In these compelling demonstrations, one typically cannot see and sometimes cannot even imagine the "absolute" motion of a given element relative to either the display screen or the retina. In one of the simplest examples, illustrated in Figure 3, a single target dot moves back and forth in a diagonal direction on a display screen, and this motion is viewed either (a) alone or (b) with two collinear surrounding dots, one above and one below, moving horizontally in phase with the target dot. Within this horizontally moving frame of reference, the target dot is now seen to move vertically, and its diagonal motion relative to the screen and eye is no longer apparent. Johansson (1974) proposed that motion perception involves a type of visual vector analysis of the motion field in terms of its common and relative components.

4. Perception of 3D structure from motion

Johansson's research significantly expanded ideas about the visual importance of relative motion as departures from common motion. Thus, motion and spatial relations may be defined by the *intrinsic* structure of moving optical patterns, as emergent properties of the spatiotemporal field rather than the local elements. The power of such intrinsic field structure in visually defining *space* is demonstrated by the following phenomena.

Kinetic depth effect (KDE)

Both the spatial structure and motion of a pattern may be defined in a 3D space rather than restricted to the 2D retinal dimensions. When one views a moving pattern that is the 2D projection of a connected 3D structure, then under a wide range of conditions one can immediately see the moving 3D form specified by the projected 2D motion pattern. A frequently cited demonstration was by Wallach and O'Connell (1953), who named it the "kinetic depth effect", though essentially the same experimental results had been reported earlier by Metzger (1934). Research on the KDE and its relatives expanded explosively beginning in the 1970s with the availability of laboratory computers, and this soon constituted a main topic area in research on visual perception (for reviews, see Braunstein, 1976; Todd, 1995).

The evident visual importance of these phenomena attracted wide interests of researchers outside the Gestalt tradition (e.g., Ullman, 1979; Marr, 1980). The rapid growth of this research area, its merging with other streams of research and theory on other topics in vision, and the infusion of new ideas from outside Gestalt traditions produced new lines of research and thinking that often had little resemblance to a Gestalt ancestry. The following are a few of the important findings about the KDE.

Two frames are sufficient

3D form and motion may be perceived with as few as two successive frames (Lappin, Doner, & Kottas, 1980; Doner, Lappin, & Perfetto, 1984; Todd, Akerstrom, & Reichel, 1988). Todd and Bressan (1990) showed both theoretically and empirically that two frames are sufficient for discriminating rigid from nonrigid motion. If nonrigidity is produced by stretching a shape only in its depth axis, however, then such nonrigidity is not perceivable (Norman & Todd, 1993). More than two frames might in principle permit perception of Euclidean structure, but observers seem to obtain little or no spatial information beyond that provided by two successive frames (Todd et al, 1988; Todd & Bressan, 1990; Todd & Norman, 1991; Norman & Todd, 1993).

Perceived surface shape

The local shape of the simulated smooth surface rotating in depth is accurately perceived under a wide range of conditions (van Damme & van de Grind, 1993, 1994; Perotti, Todd, Lappin, & Phillips, 1998; Lappin & Craft, 2000). The surface curvedness – its scale in depth – is not optically specified, however, and is not judged consistently (Koenderink & van Doorn, 1991; Todd, & Norman, 1991; Norman &Todd, 1993; Tittle, Todd, Perotti, & Norman, 1995). Some research suggests that metric surface structure can be accurately discriminated under certain restricted conditions – when the moving structure is confined to a surface of revolution, so that rotation in depth does not alter the coordinate transformation that maps the surface onto its image (Lappin & Fuqua, 1983; Lappin & Love, 1994; Lappin & Ahlström, 1994). Wagemans & Tibau (1999) however, obtained results that challenge the conclusions of Lappin and colleagues about the acuity for metric relations in 3D.

Disappearance of perceived relative motion

Under certain conditions, the simulated 3D surface may appear perfectly rigid with no detectable relative motion among the displayed points – when the viewer's head is moved and the simulated surface remains stationary relative to the laboratory room (Rogers & Graham, 1979; van Damme & van de Grind, 1993). This is a surprising phenomenon because it involves no subjectively perceived motion at all, even though the object's images on both the display screen and the observer's retina are deforming and, in fact, these image deformations are what enables the perception of 3D structure.

Students and researchers alike sometimes still regard the KDE phenomenon as a type of illusion or visual trick that distorts an objective 2D reality. This view fails to recognize, however, that the 3D structure is specified (up to an ambiguity about the relative scale of the depth dimension) by the deforming image structure. The image motions constitute *information* about the 3D structure and motion. Identifying this image information is not a trivial task, however. Suitable descriptions of the spatial structures of both objects and their images are required in order to reveal the isomorphism between objects and their images. Fortunately, this basic theoretical problem has now been solved, at least for the case of moving surfaces (Koenderink & van Doorn, 1992; Lappin & Craft, 2000). The invariant corresponding spatial structure of surfaces and their images is based on the local shape.

5. Optic flow and guidance of locomotion

Another important line of development in understanding the visual information contained in moving images was associated with the "optic flow" produced by moving observers. In the everyday visual world, animals are not merely passive recipients of moving images; they are active generators of them. The visual world is structured not only by the surrounding environment but also by the animal's movements through the environment. The momentarily visible environment is dynamic, altered by the animal's purposive movements.

The kinematics of "optic flow" are essentially the same as those underlying the perception of "structure from motion", since both involve the same image deformations. The theoretical and experimental study of the optical effects of active observer movements, however, constitutes one of the important modern extensions of the early Gestalt research on motion perception.

J.J. Gibson's ideas about "optic flow" and "ecological optics"

In three influential books, James Gibson (1950, 1966, 1979) developed the rationale for a new research program aimed at clarifying the properties of optical stimulation that enabled the visual perception of environmental structure. One of his basic ideas was that the temporal dimension of the optical field was a fundamentally important aspect of visual information about both the environmental space and the observer's locomotion through it. The kinematic structure of "optic flow fields" produced by moving observers was analogous, he suggested, to that of a flowing fluid.

A broader set of ideas was associated with what Gibson called "ecological optics". He proposed that the study of visual perception required a new approach to optics, devoted to elucidating the properties of optical *information* for active observers. Optical information involved, he claimed, not the traditional physical description of optical energy, but its geometric patterns in space–time. Moreover, the relevant forms of these spatiotemporal patterns were said to depend on the observer's actions, and required an understanding of the mutual roles of the observer's attentions and actions and the environment's structure and constraints. Many vision researchers initially regarded Gibson's ideas as scientifically undisciplined and irrelevant, but many of these ideas, especially involving optic flow, now have become part of the main fabric of contemporary vision research. The Gibsonian approach is an influential offspring of Gestalt psychology.

Differential geometry of surfaces and their images

A significant advance in the clarity and power of Gibson's ideas about optic flow and ecological optics was provided by applications of differential geometry to these topics by Jan Koenderink and Andrea van Doorn (e.g., 1975, 1976a, 1976b, 1980, 1982, 1987, 1991, 1992, 1993; Koenderink, 1984a, 1986, 1987). A key idea was that retinal images are images of smooth surfaces. Surfaces and their images both are 2D manifolds whose spatial structures are described by differential geometry. The changing retinal images produced by movements of surfaces relative to the observer may be characterized by the spatial derivatives of the motion vector field. The first-order derivatives of the 2D motion field correspond to changes in the slant of a local surface patch; and the 2D second-order differential structure specifies the local shape at any point on the surface. The space-differential structure of the surface and its image are essentially *isomorphic* (Koenderink & van Doorn, 1992). Thus, the differential structure

of the changing retinal images constitutes *information* about environmental surface shape. Moreoever, experiments on visual acuities for detecting image motion and binocular disparity recently found that human vision is directly sensitive to this form of retinal information about local surface shape (Lappin & Craft, 2000).

The potentially visible structure of objects

Another related contribution was Koenderink and van Doorn's (1976; Koenderink, 1983, 1984a, b) analysis of the singularities of the visual map between a surface and its image and the changes in these singularities as the observer explores an object by moving to a different viewpoint. (A "singularity" is a point or contour in the image at which the spatial derivatives vanish, corresponding to an image position at which the visual direction is tangent to the surface.) Koenderink and van Doorn (1976) showed that there are only three possible singular contours – fold, cusp, and T-junction. The visible singularities specify the qualitative structure of a given generic view of an object. The power of these singularities is illustrated in Figure 4a, where a number of folds, a cusp and a T-junction suffice to specify a female body. Such singularities have been used intuitively by artists in line-drawings.

An object partitions the space around it into stable viewing-regions, each containing a different set of visual singularities. Within each region, movements of the observer's viewing position do not change the number and kind of singularities, but movement into a different region provides a different set of singularities. At the transition from one viewing region to another, the singularities change catastrophically as new object parts come into view and others disappear. Any given object affords a characteristic set of generic views and characteristic transitions between these views. If one symbolizes the different generic views of a given object as circles and the transitions between generic views as lines, then the qualitative "visual potential" of the object can be described as a graph structure. Koenderink and van Doorn (1979) proved that this graph is always two-dimensional for any three-dimensional object. In Figure 4b we reproduce Koenderink's (1984b) graph of the visual potential of a tomato.

Visual guidance of locomotion by optic flow

Another of Gibson's important ideas was that the optic flow field produced by a moving observer provides rich visual information about the observer's

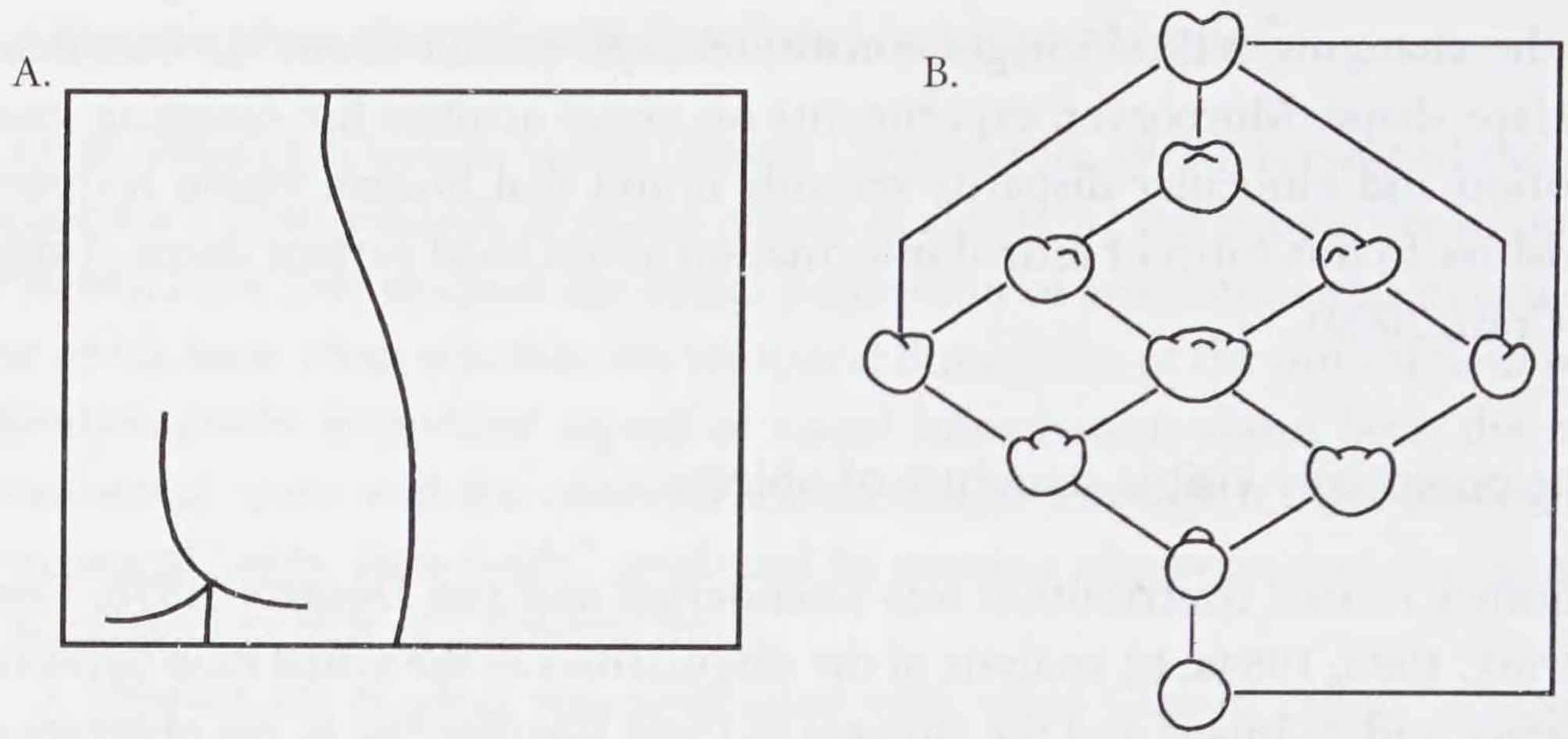

Figure 4. **A.** Free hand copy by one of the authors of a drawing by Pablo Picasso entitled "Fragments of the body of a woman". The drawing illustrates beautifully how very few folds, a cusp, and a T-junction are sufficient to see 3D form in a 2D image. **B.** The visual potential of a tomato, from Koenderink (1984b).

position and movement trajectory through the environment, and that this information must be used in guiding locomotion (Gibson, 1950, 1967). When Gibson first described this optical information for locomotion, relevant theoretical and empirical research were not available. Now, however, no one doubts the fundamental importance of this aspect of vision. A large and growing body of research describes the spatiotemporal form of this optical information and the visual sensitivity to it. (For reviews, see Regan, 1986; Warren, 1995; Warren, 1998; Lappe, Bremmer, & van den Berg, 1999.)

Perception of "biological motion"

Johansson (1973) introduced beautiful demonstrations of what he called "biological motion" – the complex kinematic patterns produced by the movements of animals. Johansson attached small lights to the major joints of active humans who were otherwise invisible except for the lights, and made movies of the patterns they produced by walking, dancing, running, riding bicycles, etc. In a single frame neither the persons nor their actions are recognizable. When they are seen in motion, however, the purposive human actions are immediately visible (Johansson, 1976). Not only is the action identifiable in a pattern lasting only a small fraction of a second, but the gender (Kozlowski & Cutting, 1977), the individual human actor, and even the actor's emotional state (Walk & Homan, 1982) also are typically recognizable by the movement style. More-

over, the recognition of such biological motion is undisturbed by many manipulations of the component elements, such as varying their contrast polarity or binocular disparity or camouflaging the patterns in random texture noise which renders them invisible when stationary (Ahlström, Blake, & Ahlström, 1997). Even cats (Blake, 1993) and four-month human infants (Fox & McDaniel, 1982) have been found to be sensitive to such kinematic patterns. Theoretically, the kinematic structure of these biological motion patterns might seem much more ambiguous than that of the original common fate demonstrations, but the visual system has no difficulty in detecting their coherent structure and motion.

6. General conclusions about sensitivities to moving image structure

In light of the many visually compelling demonstrations and extensive experimental evidence of visual sensitivity to a rich variety of spatiotemporal forms, the early Gestalt investigators' intuitions about the perceptual importance of phi motion and common fate seem remarkably insightful. At least three general lessons about spatial vision might be learned from the converging lines of research described above:

1. *Vision is sensitive to spatial structure in moving images*
Perhaps the most general lesson from the many research results summarized above is that vision is extraordinarily sensitive to coherent spatial forms in moving images. The visual forms seen in many of these experiments are emergent properties of the spatiotemporal field, defined by the relational structure of the field rather than by local optical properties as such.

2. *Visual space is shaped by moving objects and moving observers*
The spatial continuum of visual perception is shaped by the moving optical stimulation, not by spatial coordinates permanently attached to the visual receptors and neurons. The idea that visual space is structured by the visual anatomy usually has been implicit and occassionally explicit in both early and modern research on spatial vision. Considerable evidence now supports the alternative idea that space is visually defined by spatiotemporal optical fields associated with observer-habitat interactions. The image motions produced by active observers serve to coordinate the space–time of stimulation with the space–time of motor intentions and actions.

3. *The structure of moving images is information about the structure of environmental objects*

Köhler's proposal (1929) that the spatiotemporal structure of physiological activity in the brain must be isomorphic with that of optical stimulation has seemed naive from the perspectives of modern computer technology, neurophysiology, and visual science. Nevertheless, an understanding of how the perception of spatial form can be derived from optical images has not emerged from these perspectives. Westheimer (1999) recently concluded that "the idea of isomorphism, albeit in much more sophisticted forms, lives on" in contemporary visual neuroscience, partly because "the enigma of perception persists" (p. 7). Recent research on the spatial correspondence between environmental surfaces and their retinal images and on the visual acuity for such image structure indicates that spatial isomorphisms between environment, retinal images, and brain may indeed be critically important for spatial vision. The spatiotemporal field structures produced by moving images may be a primary form of information for spatial vision.

7. Neural mechanisms – an open problem

The preceding conclusions about visual sensitivity to spatiotemporal patterns seem incompatible with most contemporary descriptions of the neural mechanisms. The receptive fields of neurons in the early stages of vision usually are believed to encode stimulus properties only at restricted retinal locations. Global patterns usually are thought to be represented only at higher neural levels, not in the initial image encoding as suggested by the discussion above.

Lappin and Craft (2000) recently concluded that image information about local surface shape must be "directly" represented at the retina. This conclusion was based on hyperacuities[2] for both relative stereoscopic acuities and relative motions among spatially separate features. Such spatial relations could not be reconstructed at higher neuronal levels if they were lost at the retina. Physiological support for the retinal encoding of such spatial relations is now lacking, but perhaps the necessary experiments have not yet been done. Electrophysiological evidence of long-range interactions among retinal ganglion cells has been known for some time (McIlwain, 1966; Ikeda & Wright, 1972; Krüger & Fischer, 1973; Fischer, Krüger, & Droll, 1975; Fischer & Krüger, 1980), but the psychophysical effect of these interactions in encoding the spatial structure of moving images is not yet known.

New ideas about how neural responses carry information about the spatiotemporal structure of stimulation may be needed. The visual information carried by a neuron usually has been described in terms of its receptive field and by the selectivity of its firing rates to particular stimulus parameters such as retinal position, contrast, spatial frequency, and motion. Firing rates usually have been described over temporal intervals that are one to three orders of magnitude longer than an individual spike. The fine-grained temporal structure can hardly be retained in such descriptions. Interest in the fine-grained temporal structure of spike-trains and in alternative analyses of this temporal structure is relatively new – e.g., Sbarbati and van de Grind (1978), Wörgötter and Funke (1995), Mainen & Sejnowski (1995), Funke and Wörgötter (1997), Rieke, et al. (1997).

Information carried by the temporal structure of spike trains depends on the reliability of responses to the same stimuli as well as on differences in responses to different stimuli. The little evidence now available indicates that the temporal structure of spike trains may be rather precisely controlled by the temporal structure of stimulation (Mainen & Sejnowski, 1995; Rieke, et al., 1997), and more reliable than indicated by some previous analyses of maintained response rates (e.g., Frishman & Levine, 1983) and tuning functions (e.g., Richmond, Gawne & Jin, 1997).

Consider the spike trains produced by repeated presentations of the same moving stimulus pattern. One example of such data is shown in Figure 5. These data are from a single retinal ganglion cell of a cat, and were collected recently by Bart Borghuis and Martin Lankheet at Utrecht in collaboration with the present authors. Figure 5A shows the response pattern produced by a pattern of randomly positioned vertical bars of randomly varying widths moving horizontally through the cell's receptive field. Each row of dots in Figure 5A gives the temporal sequence of spikes produced by the presentation of the same moving random-bar pattern, and the 20 rows of dots in each section give the spike trains evoked by 20 independent presentations of the same stimulus pattern. The 8 vertically separated sets of spike trains correspond to 8 different contrasts descending in successive 10% values from 70% at the top to 0% at the bottom – with the 0% value representing a blank control pattern of the same luminance. The arrows at the top of the figure indicate the start of the repeating random-line pattern. Figure 5B shows the relation between stimulus contrast and the mean spike rate for this cell.

As may be seen, the temporal pattern of spikes reflected the spatial pattern of the moving stimulus. Moreover, separate presentations of the same stimulus generally yielded very similar patterns of responses. This inter-trial correlation

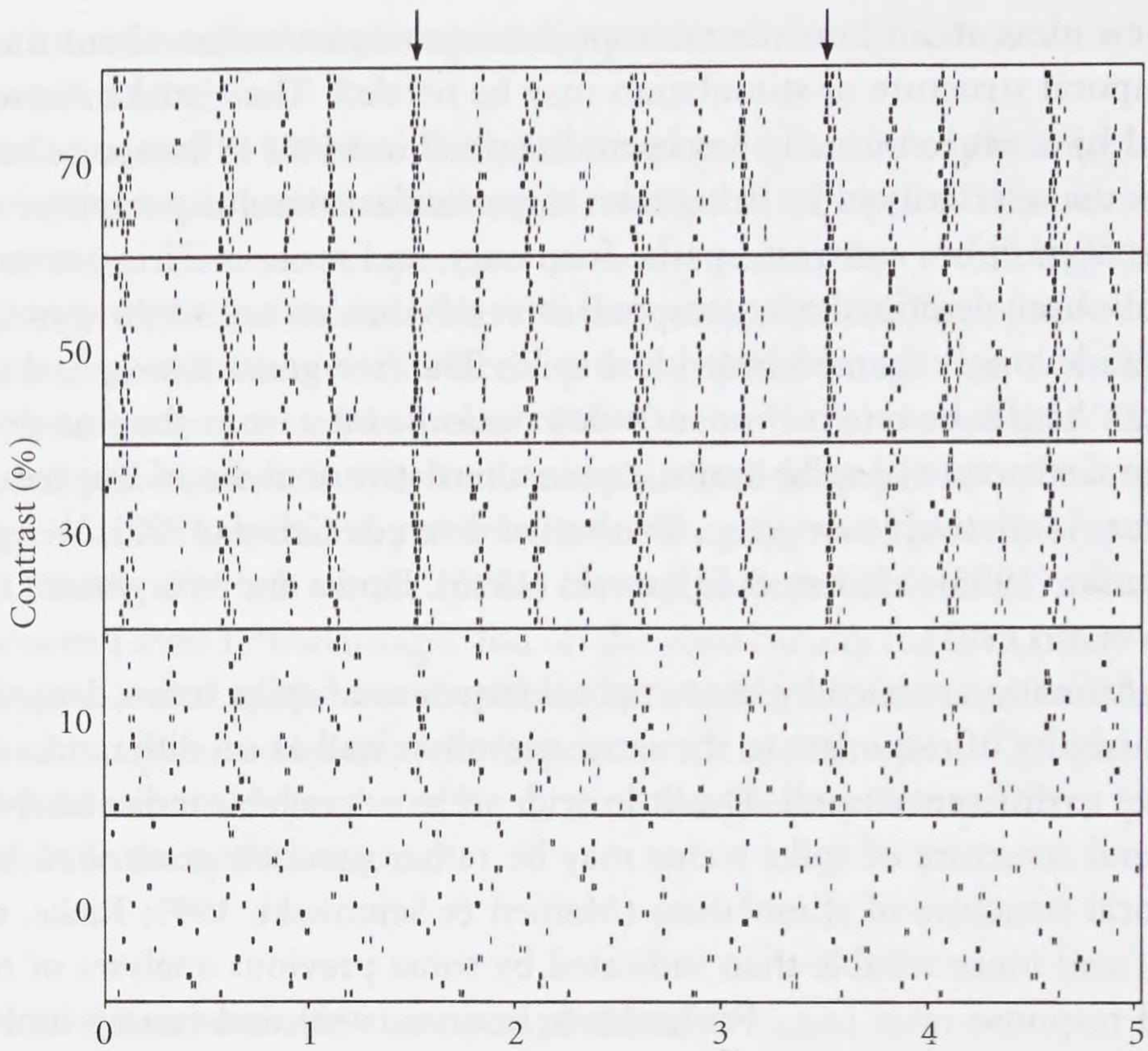

Figure 5A. Illustrative examples of temporal response patterns from cat retinal ganglion cells produced by the motion of a random-line pattern (with randomly varying widths and positions of lines) moving through the receptive field of a single retinal ganglion cell (X-ON type) of a cat. **A.** The temporal spike trains produced on 20 independent presentations of the same random-line pattern. Each row of points within each section corresponds to a different trial. The spatial positions of the points represent the temporal positions of the spikes. The five horizontal sections correspond to the responses produced by different contrasts, from 70% at the top to 0% at the bottom. The 0% value corresponds to the blank control pattern.

decreased at the lowest contrast level, however, and disappeared for the 0% control stimulus. Two different cells stimulated by the same stimulus pattern usually produced similar temporal patterns of responses (although we have not yet quantified these visually evident correlations).

The stimulus contrast affected the correlation between response patterns to the same stimulus pattern on different trials, and it affected the firing rate, but the basic temporal pattern of the spikes appears to be unchanged by variations in contrast. The firing rate of the cell carries less information about the stimulus pattern, however.

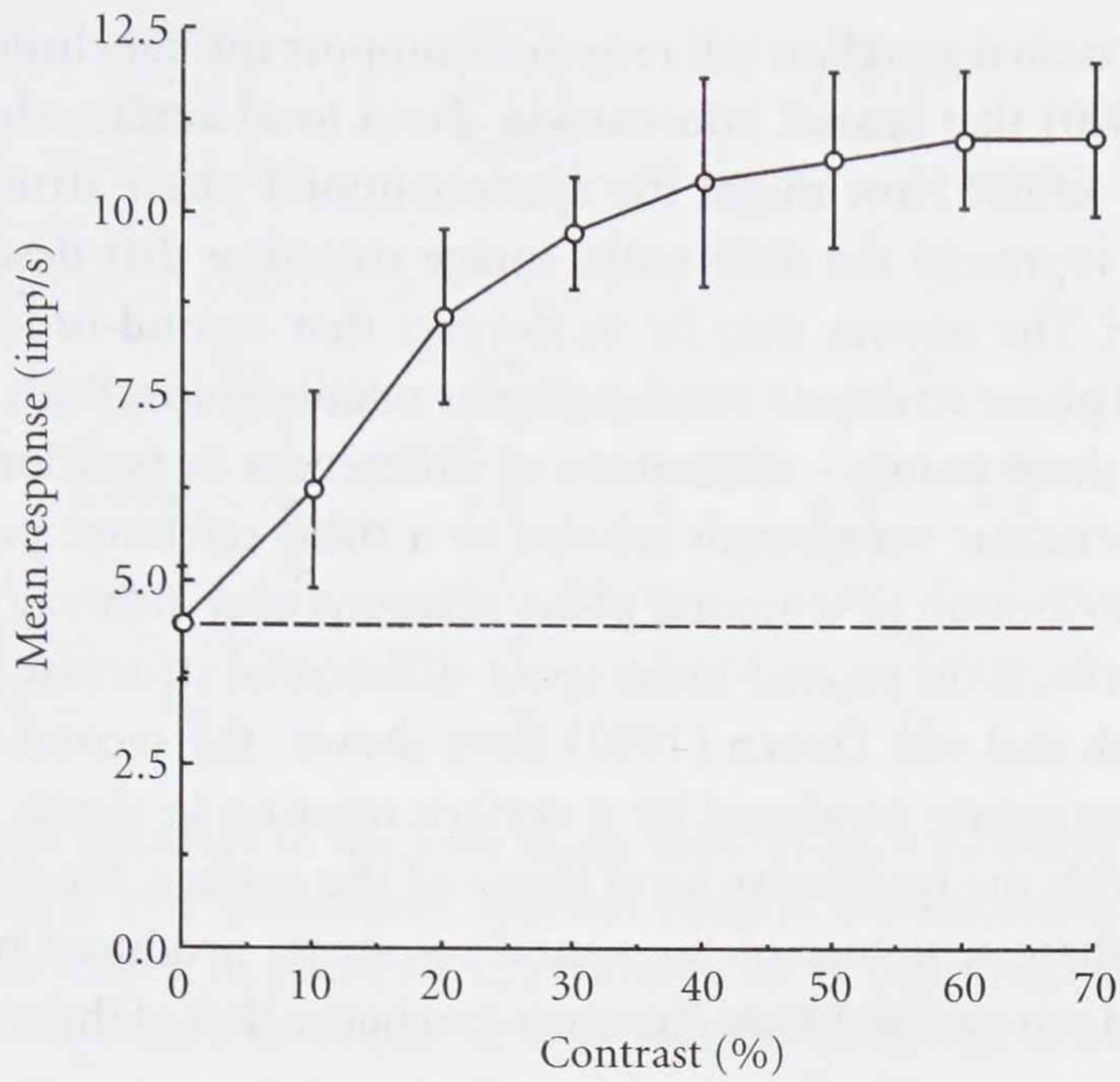

Figure 5B. The average firing rate produced by the eight different contrasts. Error bars correspond to ±1 standard deviation. (Data collected by Bart Borghuis and Martin Lankheet).

The data in Figure 5 also illustrate how the temporal pattern of responses was controlled by the spatial pattern of the moving stimulus. That is, image motions convert spatial structure to temporal structure. Even single neurons can describe the spatial structure of moving images. These temporal response patterns reflect the combined effects of the spatial scale and image velocity, but this ambiguity is reduced by active eye movements that alter the speed and direction of image motion.

Now consider how such temporal response patterns would be distributed over an array of neighboring ganglion cells. As a given stimulus pattern moves over the receptive fields of neighboring neurons, the response patterns of these cells will be correlated but temporally offset relative to one another. The temporal phase relations both within and among neighboring cells will depend on the spatial pattern of stimulation as well as on the directions and velocities of motion. Thus, information about the spatiotemporal structure of stimulation will be carried by the spatiotemporal fields of neural responses. These neural response fields may persist under motion from one retinal location to another.

Can such retinal ganglion cell responses support the conclusion by Lappin and Craft (2000) that spatial information about local surface shape is represented at the retina? How might the spatiotemporal phase structure of neural responses represent the differential image structure that describes a local surface shape? The answer may lie in the fact that second-order differential structure and phase structure involve similar relationships. Both involve relations among three points – differences of differences in position, or the position of a particular wavelength relative to a third reference point. That is, the spatial distribution of temporal phase relations over an array of neighboring neurons reflects the second-order space-differential structure of the image. As Koenderink and van Doorn (1992) have shown, the second-order differential image structure produced by a surface rotating in depth is essentially isomorphic with the qualitative local shape of the surface. Similarly, the spatiotemporal phase structure of the neural responses produced by this image would seem to mirror this image structure and hence that of the environmental surface.

Figure 6 provides an illustration of the several different 2D patterns of images produced by rotation of surfaces in depth. As may be seen, the four different categories of local surface shape yield qualitatively different patterns of image motion. And these four different types of patterns are invariant under changes in first-order spatial scale produced by translation of the surface in depth or by changes in surfaces slant. Presumably, structurally similar patterns are represented by the spatiotemporal phase structure of the neural responses, although such physiological response patterns have not yet been directly observed.

The preceding ideas about how visual neurons carry spatial information are necessarily speculative. The physiological data shown above are preliminary and extracted from a larger study. Much more work remains, but perhaps one can begin to see how the spatiotemporal structure of visual neural responses might carry information about the structure of optical stimulation and about the shape of environmental surfaces. In any case, the visual system seems to be highly sensitive to the structure of moving stimulus patterns as a source of information about the visual world.

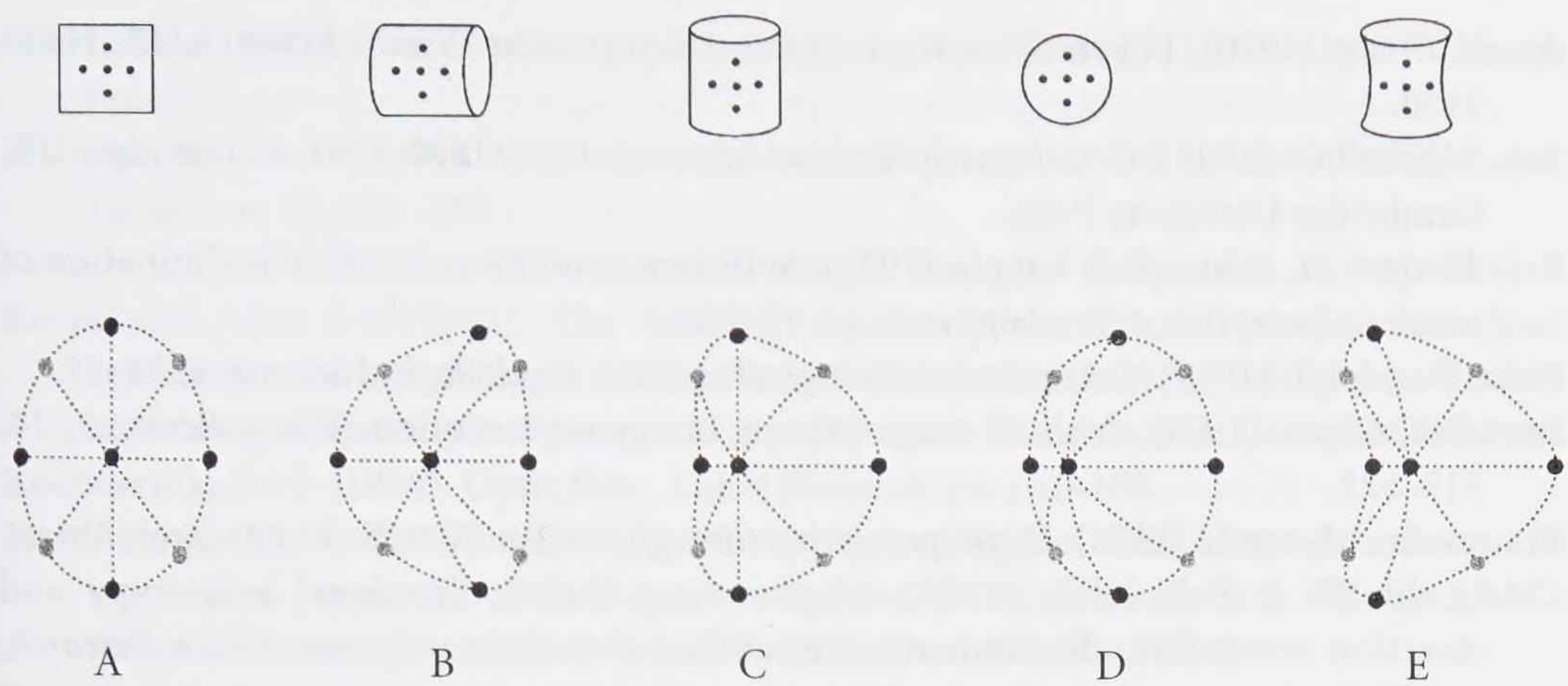

Figure 6. Spatial structure of the local image deformations produced by rotation of a surface in depth. Five qualitatively different patterns corresponding to four different local surface shapes. **A:** planar; **B, C:** parabolic (flat in one direction, curved in the perpendicular direction); **D:** elliptic (curved with the same sign of curvature in two perpendicular directions); **E:** hyperbolic (saddle-shaped, with opposite signs of curvature in perpendicular directions). The local shape at every point on a smooth surface is one of these four types. The axis of rotation in these figures is vertical. The central point is taken as a reference, with the relative motions of the other points defined relative to this reference. These patterns are those for the special case in which the local surface patch is tangent to the axis of rotation and parallel to the image plane, but the qualitative second-order structures of the images for general orientations of the surface relative to the rotation axis and image plane are essentially the same. (Adaped from *Vision Research, 37,* J.S. Lappin & W.D. Craft, "Definition and detection of binocular disparity," p. 2955, Copyright 1997, with permission from Elsevier Science.)

Notes

1. This paper was written during the first author's appointment to the F.C. Donders Chair at Universiteit Utrecht, and reflects the intellectual stimulation and research opportunities that this afforded.

2. *Hyperacuity* is the term coined by Westheimer (1975) to designate discriminations of differences in spatial position smaller than either the optical diffraction limit, the resolution limit of the human eye, or the separation between photoreceptors.

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CHAPTER 5

Tactile object perception and the perceptual stream

Roberta L. Klatzky and Susan J. Lederman

Some time ago, we, along with Catherine Reed, suggested the following *Gedanken Experiment*. First, think of the attributes you would expect to see if you were looking at a cat. You would probably first think of the visible parts (e.g., four legs, tail whiskers), perhaps imagining their particular shape or size. Next, suppose you were touching a cat without being able to see it. Which attributes now come to mind? You would be likely to think of the softness of the cat's fur, the warmth of its body, or its movement as it breathed (Klatzky et al., 1987:356). This thought experiment suggests that the phenomenological experience of an object that is perceived through touch is different from the corresponding experience when vision is present. The experience of touching a distal object, which has a number of consciously accessible properties, is the culmination of a haptic perceptual processing stream. In the present chapter we present a somewhat speculative version of that stream, based on our ideas about the relative accessibility of haptic properties and the mechanisms by which they are perceived.

1. Definition of haptic perception

The term haptic perception is an encompassing one, referring generally to perceptual responses that are mediated by receptors underneath the skin's surface. Following Loomis and Lederman (1986), we divide touch into two broad sub-domains. One domain is cutaneous, which relies on receptors in the epidermis, dermis, and underlying tissue. The other domain is kinesthesis, which relies on receptors in muscles, tendons, and joints. A variety of receptors within each of the sub-domains have been identified.

With respect to the cutaneous receptors, among the most important for object perception are the mechanoreceptors, which respond to pressure on the skin. These are generally divided into four groups, representing the crossing of two variables: size of receptive field (area of skin surface to which a given receptor responds when pressure is applied) and rate of adaptation to continued pressure (rapid or slow). Thus there are receptors that have large receptive fields and adapt rapidly, others that have small receptive fields and adapt slowly, and so on. In addition to the mechanoreceptors, there are thermoreceptors that code steady-state cool and warm skin temperatures and changes in skin temperature due to heat flow between the skin and surrounding media.

2. Successive descriptions of surfaces and objects in haptic perception

In general, perception can be characterised as interactive processing involving multiple representations that are realised at distinct neurological loci. Functional and neurophysiological analyses support the idea that perceptual processing feeds forward as a cascade (McClelland, 1979) but has feedback that allows for interaction among levels. One can distinguish between early and late representations, in terms of when they are formed during the course of the perceptual stream. In general, later representations tend to be functionally more abstract, in that they are mapped into by a wider variety of physical stimuli. Early visual descriptions, for example, are view-specific and-edge based, whereas at least some models of visual pattern recognition describe later, higher-order representations as abstract, volumetric, and object-centred (e.g., Biederman, 1987; but cf., e.g., Tarr and Pinker, 1989). Describing a functional perceptual system involves defining the different levels of representation that are formed, and showing how they are related to one another in terms of successive derivation and subsequent interactions.

Within this approach, we make a coarse set of distinctions between three levels of representation of objects and surfaces in haptic perception. (1) There are *sensory primitives*, which are provided directly by populations of cutaneous and kinesthetic receptors. (2) An intermediate-level representation comprises consciously accessible *perceptual properties*, such as particular degrees of hardness or roughness. These properties are derived from the sensory primitives. (3) At a higher level of abstraction still are the representations of whole *objects*, which comprise collections of properties. Thus, in order of abstraction, we have sensory primitives, derived perceptual properties, and objects. In this section we will describe each level of representation in more detail.

2.1 Sensory primitives

The haptic receptors give rise to a set of primitive sensory features. These primitives are the output of populations of receptors, which respond to attributes of objects and surfaces that are contacted. Sensory primitives can be subdivided according to whether the relevant receptor population is cutaneous or kinesthetic.

Populations of cutaneous receptors provide the following sensory primitives about points of contact with an object or surface: (i) a pressure array on the skin, (ii) vibratory presence and frequency, and (iii) apparent temperature. We will discuss each briefly.

An array of sustained local pressure on the skin

This is mediated by slowly and rapidly adapting mechanoreceptors with small receptive fields. The SAI (Slowly-Adapting Type I) receptors, associated with the Merkel disks, are capable of resolving points separated by approximately 1 mm. The responses of these receptors code a pressure array that can be used to compute spatial properties of surfaces, as we describe in more detail below. The rapidly adapting FA1 (Fast-Adapting Type I) mechanoreceptors, associated with Meissner corpuscles, code the rate of change of pressure on the skin, which is correlated with the spatial properties of the touched surface (Srinivasan and LaMotte, 1991). Receptors with larger receptive fields are of limited use in conveying precise information about the pressure array on the skin.

Presence and frequency of vibration

This is mediated particularly by the class of rapidly adapting mechanoreceptors with large receptive fields, the FAIIs or Pacinian Corpuscles. This type of receptor, located deep within the skin, exhibits a sharp tuning function with peak sensitivity at 250–300 Hz. Coarse coding of the frequency of a stimulus train could be produced by variations in the magnitude of the receptor response and/or by entrainment of the neural impulse with the input frequency. The simple presence of vibration, with coarse information about frequency, could be coded by other mechanoreceptors as well as the Pacinians. In particular, the FAI receptors are maximally sensitive to low-frequency stimuli, with peak sensitivity around 40 Hz.

Apparent warmth/coolness

This is mediated by the thermoreceptors, of which there are two subtypes. Warm fibers give a sustained response to temperatures at approximately 30–

50°C, decreasing their response as the temperature decreases. Cold fibers respond in the range of approximately 10–40°C, decreasing as temperature increases.

The role of the receptors of the kinesthetic system is less well understood than those of the cutaneous system. Hence the sensory primitives of kinesthesis are more difficult to determine. Signals from muscle spindles, Golgi tendon organs, and joint receptors provide information that will ultimately lead to the perception of limb position, joint angle, and more complex joint configurations or patterns of extended movement. However, the chain of processes that leads to perception of these derived properties is far from well understood. We will therefore concentrate on cutaneous primitives and perceptual properties derived from them.

2.2 Derived perceptual dimensions and properties

The primary focus of our work has been on an intermediate level of representation, constituting properties derived from the sensory primitives. We use the term *dimension* to refer to the aspect of an object or surface that is coded (e.g., roughness). When instantiated in a particular object, dimensions take on specific values, in which case we call them *properties* of the object.

We have made a basic distinction between geometric and material dimensions (see, e.g., Klatzky and Lederman, 1993b). This distinction is made by materials scientists, who define a material dimension as one that relies on the substance from which a sample is made but is not dependent on the particular sample that is being examined. In contrast, a geometric dimension describes the spatial characteristics of the specific sample.

Within the material category are surface dimensions (roughness, slipperiness, and the like), compliance, and thermal dimensions (apparent warmth or coolness). The principal geometric dimensions are size, shape, and orientation within a frame of reference. The weight of a free-standing object is a hybrid that reflects both its material (density) and geometry (size, e.g., as measured by area of the envelope, and shape, e.g., hollowness).

Whereas the distinction between material and geometric dimensions is concerned with their content, one can also distinguish between the way in which they are coded. Content and code are related, but not synonymous.

Lederman and Klatzky (1997) suggested that perceptual dimensions can be coded in two fundamentally different ways. One way is *intensive*; that is, the property value is coded as a magnitude along some underlying single dimension. Another way of coding a perceptual dimension is *spatially*; that is, the

property value is coded with reference to the layout of elements within a spatial co-ordinate system.

Consider first some examples of intensively coded dimensions. Cutaneously sensed roughness appears to be coded intensively. Models of perceived roughness have related it to the variability in the pressure array provided by the slowly adapting mechanoreceptors. In particular, this appears to be the mechanism for roughness perception when the elements composing a texture are spaced at greater than 1 mm (Johnson and Hsiao, 1992). When the elements are more closely spaced, the roughness percept is conveyed by rapidly adapting mechanoreceptors and is a vibratory signal rather than a spatial one (LaMotte and Srinivasan, 1991). Nonetheless, the coding is what we would call intensive, since the vibratory signal is not coded with respect to layout in space. Instead it is a single magnitude; an intensity.

The thermal receptors also provide intensive dimensions, namely, the rate at which the skin is cooled or warmed as a surface is touched, and the final temperature reached at steady state. The responses of a population of receptors appear to be summed over space to provide a robust signal of the intensity level (Kenshalo, 1984), from which the perceived property is derived.

Consider now some spatially coded dimensions. When the skin touches a raised edge on an otherwise flat surface, defining the orientation of that edge requires reference to a spatial reference system. Hence edge orientation is a spatial dimension. So too is the spatial arrangement of raised points on a surface, which is the basis for discriminating among Braille characters. These spatial codes are presumably provided by the pressure array from the slowly adapting mechanoreceptors (Johnson, 1983).

Note that the same receptor populations can provide the basis for either intensive or spatial codes. This is the case, in particular, for the slowly adapting mechanoreceptors with small receptive fields, which appear to underlie both intensively coded roughness (of textures with elements spaced > 1 mm apart) and spatially coded patterns like Braille.

Some dimensions of surfaces are ambiguous with respect to whether they are coded intensively vs. spatially. For example, a curved surface touched with the fingertip produces a discharge rate in slowly adapting receptors that directly reflects the depth to which the skin is penetrated and the change in the curvature of the skin surface as it conforms to the object surface (Srinivasin and LaMotte, 1991; LaMotte and Srinivasin, 1993). The differential responses of the receptors are mediated by differences in pressure on the skin, which arise from the shape of the touched surface. The distribution of the discharge rate over the population of receptors therefore allows the shape of the curved surface to be

coded as a spatial pattern. However, the same gradient could be coded intensively, either by the receptor responses to the peak pressure, which is inversely related to the radius of curvature, or – since the peak pressure is correlated with the total stresses and strains on the skin – by integrating the response magnitudes over space.

Whether a spatial or intensive code is used, in fact, may vary in the task context. For example, determining the axis of orientation of a cylindrical surface would presumably require a spatial code, whereas discriminating a curved surface from a flat one could be performed intensively. Lederman and Klatzky (1997) argued that when either code is used, the one that is accessible earlier will be used as the basis for response in speeded tasks.

2.3 Integrated object representations

Objects that are encountered by the haptic system have diverse properties, both geometric and material. Our phenomenological experience of a touched object is not necessarily one of contacting an array of individual properties. We can feel an object as an integrated whole. Thus, for example, the hypothetical cat described above need not be perceived as a set of discrete features like warm, soft, rough, vibrating – rather, it feels like a *cat*! Ultimately, the perceptual stream must be able to integrate properties into a coherent entity.

Although we can perceive an object as a totality of multiple properties, it also seems that we can focus differentially on properties of an object. We can, for example, focus on the cat's warmth and not attend to its smooth fur. Below, we will review evidence that achieving a focus on particular properties is accomplished in part by directing movements of the hand. That is, some properties may be emphasised and others obscured, according to the hand movements that are used in contacting an object.

We have argued elsewhere that the identification of objects through touch relies where possible on material properties, whereas the identification of objects through vision relies primarily on geometric properties. Thus touch and vision provide complementary perceptual streams for object identification. Our arguments for the differential role of material vs. geometric properties in haptic and visual object recognition go beyond the scope of this chapter. One line of evidence is described below, namely, that material properties become accessible to higher-order processing in the haptic modality earlier than geometric ones. Other findings related to the primacy of material properties in object identification by touch can be found in a series of chapters (e.g., Klatzky and Lederman, 1993a, 2000; Lederman and Klatzky, 1993, 1996).

This concludes our introduction to the three levels of object representation in the perceptual stream of the haptic modality – sensory primitive, derived perceptual property, and object. In the next section, we make three basic points about the stream of processing outlined above, based primarily on our own research program.

3. Empirical studies of derived properties and their integration into objects

The three basic points about the haptic perceptual stream that we wish to make in this section are as follows: (1) At the level of derived perceptual properties, there are differences in relative accessibility, with intensively coded properties being more accessible in general than spatially coded properties. This differential accessibility is presumably attributable to the time required to compute the property from the relevant sensory primitives. (2) Specialised hand movements are highly useful, and in some cases essential, for deriving properties from primitives. Hand movements capitalise on the motor capability of the hand that accompanies its perceptual function, and they facilitate the computation of object properties. (3) The integration of derived properties to form a whole object representation is constrained by these same specialised hand movements, which function as a form of attentional filtering.

3.1 Difference in relative accessibility of derived (intermediate-level) properties

The research described in this section makes the point that object properties are not equally accessible to the haptic perceptual stream. The idea that properties are computed, neurophysiologically, from primitives leads to the possibility that different computations take different amounts of time. This means that information about object properties will be differentially available to the ongoing perceptual stream, depending on the particular properties in question.

We studied the relative accessibility of derived perceptual properties with a variation on the well-known visual search task (e.g., Treisman and Gormican, 1988). In visual search, the subject is given a target (e.g., X) and asked to find it in a set of distractors (e.g., O's). On some trials, there is a single target among the distractors; on other trials there are only distractors. The number of items in the display (target plus distractors) is varied, and the response time is determined as a function of display size. For some target/distractor combi-

nations, the resulting function is flat, indicating that the target can be found as easily when there are many distractors as when there are none. The target is sometimes said to 'pop out.' This is the case, for example, when an X is sought among O's. For other target/distractor combinations, the response-time function is increasing, and the target is said to be found by search. While the slope of the response-time function is generally the focus in visual search, the intercept is also of interest, because it may reveal processes that are independent of the number of items in the display, but that are nevertheless dependent on the particular target/distractor combination that is being used.

Whereas Treisman and Gormican (1988) used the search task to investigate which visual properties could be considered perceptual primitives, we used the same paradigm to address a related issue – the relative accessibility of object properties over the course of perception. Our version of this task (Lederman and Klatzky, 1997) was haptic search, where one target was presented to each of 1–6 fingers (the three middle fingers of each hand). This was accomplished by a computer-driven apparatus that prepared the displays for each finger by selecting them from a rotating drum, then lifted all the displays to the fingers simultaneously (Moore et al., 1991). On each trial, the subject was given the identity of a target feature to be found among a set of distractors; for example, a rough surface that might occur in the presence of smooth surfaces. The number of items in the display varied from 1 to 6, and the target could be present or absent. With one exception, target/distractor combinations were tested in both directions in different conditions of the experiment; for example, subjects sometimes searched for rough in smooth and sometimes for smooth in rough.

We performed, in all, some 15 experiments that varied in the nature of the target/distractor stimuli. The stimuli represented four general classes of stimulus contrasts. There were material constrasts (rough/smooth; hard/soft; cool/warm) and contrasts that represented abrupt surface discontinuities (i.e., edges), such as looking for a raised edge among flat surfaces or looking for a hole among flat surfaces. There were searches involving three-dimensional continuous surfaces that contrasted in contour, such as looking for a flat surface among curved surfaces. Finally, there were contrasts that required spatial relations to be determined, such as looking for a surface with a horizontally oriented edge among surfaces with vertically oriented edges. These last cases required spatial coding, because the stimuli were equated for the intensive nature of the display (for example, an edge has the same pressure distribution whether it is oriented horizontally or vertically).

The results of these studies were very clear. People demonstrated flat slopes – indicating 'pop out' – when the search involved discrimination of

material. For example, when participants searched for a rough surface among smooth surfaces, the slope of the function averaged 4 milliseconds across the target-present and target-absent conditions (both of which produced very flat search functions). Slopes were somewhat steeper, but generally within 30 milliseconds per item, when the search involved rough spatial discontinuities. Slopes were steepest (around 60–450 milliseconds) when the target/distractor distinction required participants to discriminate spatial relations.

There was also a tendency for the searches with shallower slopes to have lower intercepts. This positive correlation between slopes and intercepts indicates that when the search required capacity to be distributed across the fingers and the item did not pop out (i.e., the slope was relatively high), there were also time-consuming processes that occurred regardless of the number of fingers that were stimulated and that entered into the intercept of the search function. An interesting exception was the condition where the target was a cool stimulus (aluminium) and the targets were warm (pine). Here, the slope was quite flat, but the intercept was quite high, presumably reflecting the relatively slow response of the thermoreceptors to the heat flowing from the fingers to the cool object. (The same search could not even be performed in the reverse direction – warm target in cool distractors – without high errors.)

The observed pattern of slopes and intercepts – lowest for material properties, highest for spatial relations, with spatial discontinuities in between – suggests that properties that can be intensively coded become accessible for perceptual comparison faster than properties that must be coded spatially. Moreover, within the intensive properties, it appears that material properties become accessible earlier than spatial discontinuities. We concluded that there are basic differences in the rate at which the intermediate-level of haptic object representation, the level of properties derived from sensory primitives, is achieved.

3.2 Role of specialised hand movements in deriving intermediate-level properties

The next point we wish to make is that the derivation of properties at the intermediate level is the result of a symbiosis between the haptic perceptual system and the motor system. The skin is not only a covering for receptor populations, but it is also a covering for physiological mechanisms that allow movement. In other words, the perceptual and motor systems are combined in a common effector. This combination powerfully enhances the perceptual responses of the

haptic system, expanding the range of properties that can be derived from more primitive levels of representation.

Consider, for example, what happens when we wish to perceive the roughness of a surface. Typically, we do not feel the surface statically; instead we rub our fingers across it. This 'lateral motion' of the skin across the surface enhances the perceptual responses of mechanoreceptors that form the basis for the roughness percept.

This example illustrates a general pattern: For each of the various intermediate-level derived properties that we have considered, there is a characteristic pattern of exploratory motor movements that enhances it. In some cases, this characteristic pattern not only enhances the perception of the derived properties, it is actually necessary for it.

Our early work (Lederman and Klatzky, 1987) catalogued a set of basic exploratory 'procedures' and related them to object properties being perceived. We demonstrated this coupling of exploration and perception with a match-to-sample task. On each trial of the task, the subject was given a standard object and asked which of three comparison objects best matched it on a targeted object property, such as roughness, hardness, or volume. We observed the way subjects moved their hands when exploring the target object. Different target properties produced very different patterns of exploration. For example, when asked to match on surface roughness, subjects exhibited 'lateral motion' of the skin across the surface. But when asked to match on apparent temperature, subjects tended to put a large hand surface statically against the surface. This presumably enhances the spatial summation of the thermoreceptors.

We demonstrated that the observed exploratory procedure associated with an object property was generally optimal (in speed or: accuracy) and sometimes necessary for perceiving it, by instructing people to use each of the exploratory procedures with each of the object properties in the match-to-sample task. The most effective procedure used for a particular object property tended to be the one that people exhibited spontaneously. For example, when matching the target to the samples with respect to roughness, people exhibited lateral motion between the skin and object surface. When each of the exploratory procedures was tested with the roughness-matching task, this same lateral motion procedure turned out to be the optimal way of extracting roughness information.

In one case, as we have noted, an exploratory procedure was necessary to extract a particular property, in that no other procedure yielded above-chance matching performance. Specifically, when people matched the target to the samples on the basis of exact shape (independent of size), the only effective

exploratory procedure was what we call 'contour following' – movement of the fingers along the gradient of maximal change in the object contour. This same procedure that was found to be necessary in the constrained exploration task was also what subjects exhibited spontaneously, when free to explore in any way, during matching on the basis of exact shape.

While the exploratory procedures are highly visible when people do unspeeded exploration, for purposes of description or matching unfamiliar objects, practice does change the duration and style of exploratory procedures. And in some cases, particularly when people are discriminating among a small set of well-known objects, they can achieve correct responses without obviously exhibiting the optimal exploratory procedure. For example, the lateral motion between skin and surface that occurs at contact may become sufficient to perform a roughness discrimination, without additional movement that constitutes visible rubbing, when the alternative roughness values are well known and the differences between them are substantial. Lederman and Klatzky (1997) reported that for some properties, finger movements became minimal when subjects did extended periods of haptic search – although visible movement could not be eliminated entirely for difficult spatial discriminations.

Yet another demonstration of the coupling between patterns of exploration and perceptual properties is found when people are performing object identification without vision, and are driven by hypotheses about an object's identity (Lederman and Klatzky, 1990). When there is a property of an object that is particularly relevant for identifying it (a 'diagnostic property'), people will exhibit the exploratory procedure associated with that property. For example, when asked whether a pair of glasses has a plastic lens, people will use static contact with a large skin surface to check the apparent warmth of the lens. Static contact is the exploratory procedure that is found to be used spontaneously, when participants are asked to match objects according to their apparent temperature, and it is also optimal for temperature matching.

We have further documented that the same pairing of exploratory procedures with object properties is done when people have vision available, but are asked to make difficult perceptual comparisons along haptically accessible dimensions (Klatzky et al., 1993). For example, when asked which is rougher, an egg or a pear, people will explore the objects with lateral motion of the fingers. This is the same procedure that was found optimal for judging roughness in the match-to-sample task. Similarly, people use appropriate exploratory procedures for difficult judgements of weight and hardness when vision is present. However, people do *not* typically explore objects haptically when they are given difficult questions about size and shape (e.g., which is larger, a marble or a

grape) and vision is present. Vision is the preferred modality for answering these questions, and typically touch is not used at all.

In short, we have shown with several different experimental paradigms that the derivation of intermediate-level object properties capitalises on motor movements by using exploratory procedures that optimise the process. Some specific mechanisms that may underlie the coupling of exploration and perceived properties were discussed by Klatzky and Lederman (1999). In essence, we view exploratory procedures as optimising computational algorithms that compute property values.

3.3 Exploration as a mechanism for and constraint on the integration of perceptual properties

The final point we wish to make in our discussion of the haptic perceptual stream pertains to the level of processing at which derived perceptual properties become integrated into coherent objects. Our point is that the same specialised hand movements which facilitate or are even required for the derivation of perceptual properties play a critical role in the process of integration. In brief, exploratory procedures that are performed at the same time lead to an integrated object representation, and if two exploratory procedures cannot be performed together, than performance of one can effectively filter out the information that is optimally acquired by the other.

We have reached these conclusions on the basis of tasks in which people are asked to sort a series of objects into bins as quickly as possible, on the basis of some property or properties. The objects are constructed so that each object can take on one of several possible values of a number of properties. For example, in one experiment (Klatzky et al., 1989), we used objects that could take on three values of size, contour, surface roughness, and hardness. For the remainder of the discussion, we will use S, C, R, and H to refer to these properties, respectively, and a numerical index after a letter will refer to a particular property value. In these terms, then, subjects might be asked to sort on hardness so that objects with H1, H2, and H3 must be placed in different bins, but each bin combined the three possible values of S, C, and R.

Using this sorting task, we created two different manipulations, which we call *redundancy withdrawal* and *orthogonality insertion*. In the redundancy withdrawal paradigm (Klatzky et al., 1989), subjects are told to sort on one target property (e.g., H), while another property varies redundantly with the target. They are not, however, informed about the redundant property. For example, subjects might be told to sort on the basis of hardness, but they might ex-

perience objects where the only possible combinations of hardness and roughness are H1R1, H2R2, and H3R3. In this case, roughness is redundantly varying with hardness. We find systematically that the redundant property is found to speed classification, relative to sorting without the redundancy. In the redundancy withdrawal paradigm, after a series of trials with the redundant combination of properties, the redundant property is suddenly withdrawn. After withdrawal, for example, the subject sorting on hardness, but with roughness having previously been redundant, will experience objects with H1R1, H1R2, H1R3, and so on. That is, roughness is no longer a cue as to the appropriate bin for the object, because each roughness value occurs with each level of hardness. If, at the point of withdrawal of the redundant property, the response time goes up significantly, we know that the subject must have been using the redundant property along with the target property. This is evidence for integration of the two properties.

We have found that only certain combinations of properties show this evidence of integration. They are properties for which the appropriate exploratory procedures can be performed together. For example, roughness and hardness can be integrated, because subjects can move their fingers laterally (to encode roughness) while applying pressure into the object's surface (to encode hardness). But on a thin planar object, where shape information is carried on the edges, subjects find it difficult to integrate shape with roughness, which is carried on the planar surface. They cannot explore the edge, using contour following, while they apply lateral motion to the surface. Hence they show no redundancy withdrawal effect.

In the orthogonality-insertion paradigm (Lederman et al., 1993), subjects initially sort on one property while another one remains invariant. For example, they may sort on hardness while experiencing only one value of roughness, R1. Thus they would put H1R1, H2R1, and H3R1 in different bins. Now, after a series of trials, an orthogonal dimension is inserted: Subjects now experience R1, R2, and R3 while classifying on H. They must put H1R1, H1R2, and H1R3 into the same bin, H2R1, H2R2, H2R3 into a different bin, and so on. If, under these circumstances, response times go up, we have another form of evidence for integration of the two properties being manipulated. Indeed, the same combinations of properties that yield redundancy-withdrawal effects are also found to yield orthogonality-insertion effects.

4. Conclusions

The haptic perceptual system is similar to others in that it unfolds as a continuum of representations that form the basis for interactive processes. In the domain of perception pertaining to objects and surfaces, we have identified three key levels of representation. The level of object properties is derived from primitives at a sensory level, and itself provides a set of descriptive primitives for objects. We have made fundamental points about the level of object properties: The derivation of intensively coded properties, which include material and surface discontinuities, is performed faster than spatially coded properties; hence the former are more accessible. The coding of material and geometric properties makes use of the motoric capabilities of the hand, which allow for the performance of specialised exploratory procedures that optimise the computation of properties. While exploratory procedures enable the coding of properties, they simultaneously constrain such coding, providing a basic mechanism to regulate the flow of information along the perceptual stream.

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CHAPTER 6

Continuum of haptic space

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1. Introduction

The structure of haptic space has first received serious attention in 1937 by Blumenfeld. Haptic space, as used in this chapter and indeed also by Blumenfeld, involves the space around us which we can reach by touch from a fixed position. How this space is related to the space through which we navigate is an interesting question but not the topic of this chapter.

Inspired by earlier experimental results in the visual domain, Blumenfeld measured the so-called "alley curves". Subjects had to pull two threads, that were fixed symmetrically on both sides of the median plane, towards themselves such that the threads felt as parallel to each other and to the median plane. Depending on the distance to the median plane, the resulting lines either were diverging, parallel, or converging. Rightly so, Blumenfeld concluded from these results that haptic space was not Euclidean; that is, lines that are parallel in haptic space are usually not parallel in Euclidean or physical space. Moreover, since the deviations from physical space were apparently systematic and not just random, it became possible to talk about the structure of haptic space. Although Blumenfeld discussed his findings in terms of the "parallelity laws" and speculated about the underlying cause for the deformation, he did not give a formal description of his results.

Surprisingly, unlike in the visual domain, his interesting haptic experiments did not really get a follow-up. Just a few studies concerning haptic space were published (e.g., Worchel, 1951; Bambring, 1976; Lederman, Klatzky & Barber, 1985), but none of these studies directly addressed the way haptic space is deformed with respect to Euclidean space.

To our knowledge, our research is the first serious attempt to study and describe the structure of haptic space. One of the questions that had to be answered was whether it is justifiable to speak of "the structure of haptic space" at

all. For this question to be answered affirmatively, haptic space should possess a number of properties, the most important being that measured spatial relations (such as, for example, parallelity) are reproducible and that from a set of measurements predictions can be made for spatial relations at other locations by interpolation or even extrapolation. This latter property assumes that haptic space is continuous and would indicate that there is indeed an underlying structure. Once it has been established that haptic space is structured, another question is to find how it is structured, or in other words, find a formal description of the structure. These two questions cannot be answered independently, and our strategy has been to collect a large amount of data in a number of different experiments all investigating haptic spatial relations. What follows is a bird's eye view over these experiments.

2. Parallelity of rigid rods

One way to investigate the properties of haptic space is to test parallelity. Here we investigate parallelity in a way less restricted than Blumenfeld's, that is, we do not confine ourselves to stimuli equidistant or parallel to the median plane.

The set-up consisted of a large table (see Figures 1 and 2). On this table an iron plate of the same size was fixed. This plate was covered with a plastic layer on which 15 protractors were printed. The diameters of the protractors were 20 cm. In the right–left direction the spacing between the centres of the protractors was 30 cm, in the forward–backward direction 20 cm. Aluminium bars of 20 cm length and 1.1 cm diameter could be positioned on the protractors. On each bar a small pin was fixed perpendicularly to the middle of the bar and this pin fitted exactly in holes in the centres of the protractors. In this way, the aluminium bars could be rotated without being displaced. Small magnets were attached under the bars to increase their resistance to movement (hence the use of the iron plate). Small needles at both ends of the bars allowed the experimenter an accurate reading of the orientation of the bars.

Two aluminium bars were used as reference and test bar. In this first experiment, only the protractors numbered 1 through 9 were used. The reference bar could appear at any of the nine locations and the test bar appeared at all remaining eight locations. As reference orientations we used 0°, 45°, 90°, and 135° (0° is parallel to the long side of the table, and increasing values indicate a rotation in anticlockwise direction). All combinations of reference and test bar location were measured three times in random order.

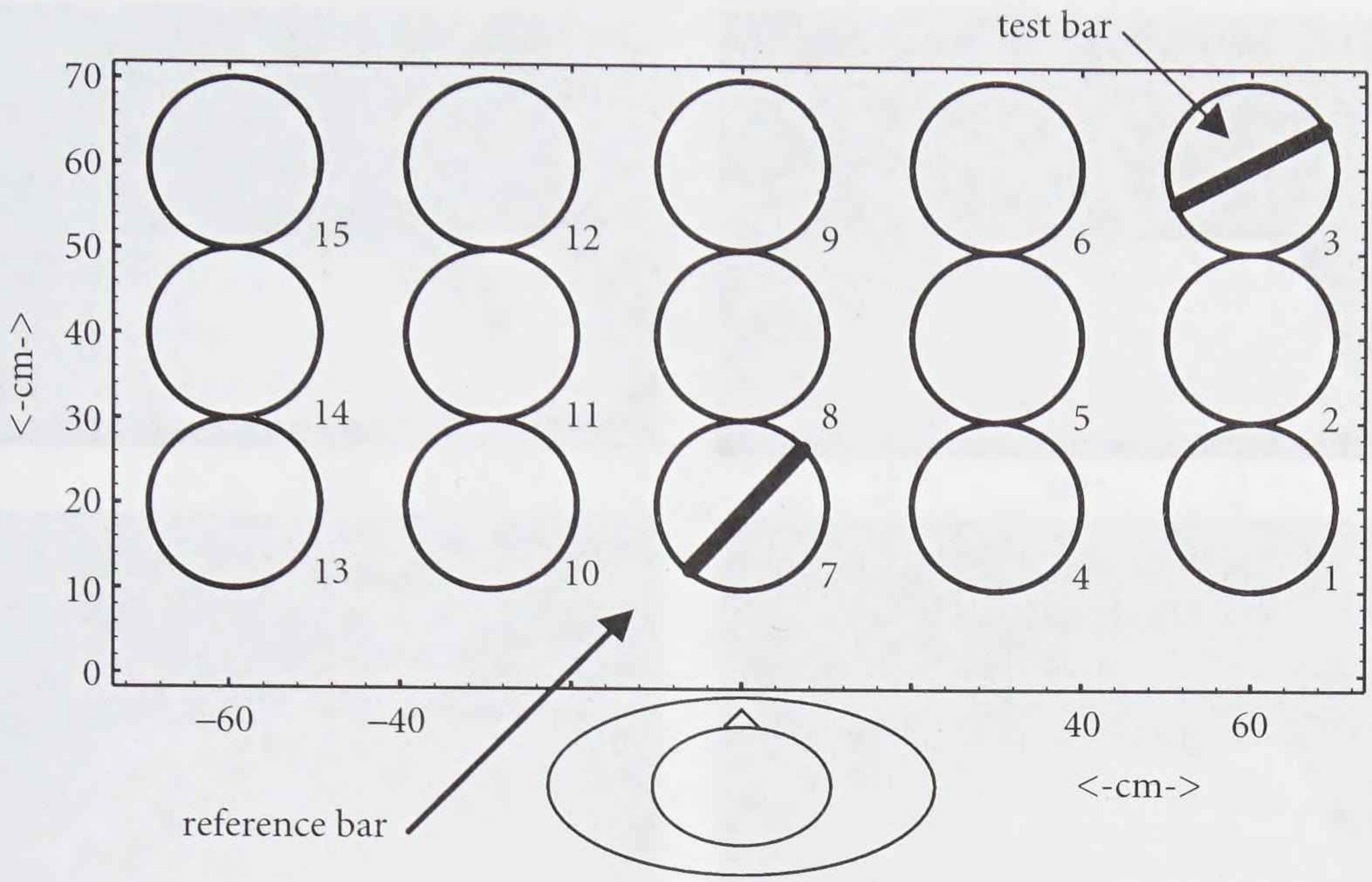

Figure 1. Top view of the set-up with a blindfolded subject seated in front it. The circles indicate protractors that allow the experimenter to measure the orientation of the bars. Bars and markers can be positioned at the centres of the protractors.

Six subjects participated voluntarily in this experiment. During the experiments they remained ignorant about the research question, the set-up, and the number of locations and orientations of the reference bar. Four of the subjects were strongly right-handed, one was weakly right-handed and one was moderately left-handed (according to the definitions of Coren, 1993).

The subjects were blindfolded before the experiments started. The experimenter positioned a reference bar at the prescribed location and under the right orientation. Subsequently, the test bar was placed with a random orientation. The subject's task was to adjust the orientation of the test bar in such a way that it felt as being parallel to the reference bar. The subject was allowed to go back and forth between the two bars as often as he or she preferred (this procedure can be seen in Figures 2a and 2b). The subjects were not allowed to touch the edges of the tables for comparison. They never received any feedback about the accuracy of their settings. The experiments took many hours per subject and were performed in blocks of about an hour.

An indication of the results can already be obtained from Figures 2a and 2b. Although the subject is still moving back and forth, the setting shown is close to her final setting. It is clear that the orientation of the reference bar (the bar closest to the subject) is different from that of the test bar. The reference

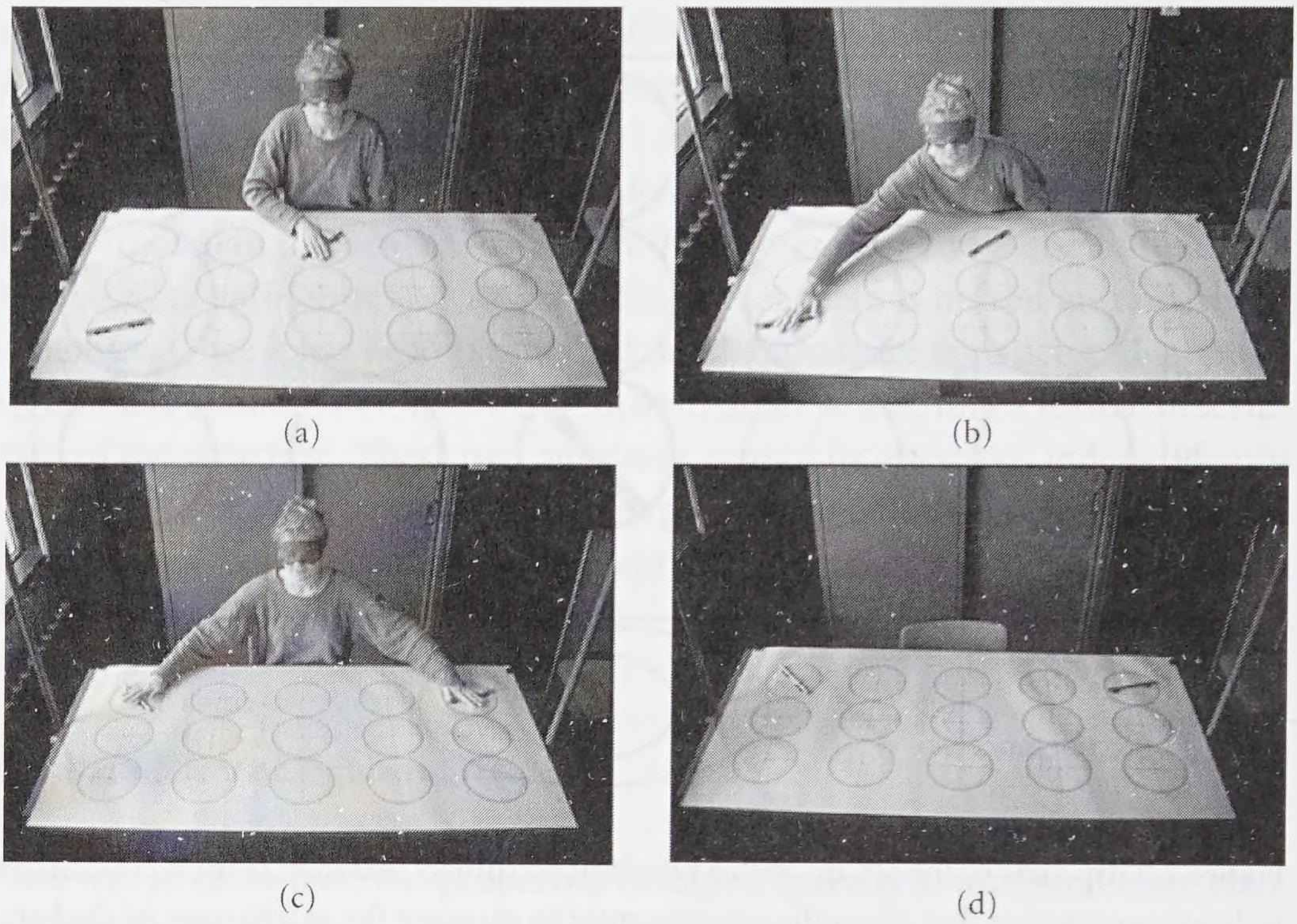

Figure 2. Photographs of a subject performing the parallelity task unimanually (a) and (b), and bimanually (c). The setting seen in (b) is close to her final setting. Her final setting in the bimanual task can be seen in (d).

bar's orientation is 45° whereas the test bar's orientation must be about 20° (estimation from the photograph). Interestingly, the settings of other subjects always deviate in the same direction.

A more detailed and accurate presentation of the results is given in Figure 3. The representative results shown are obtained by subject ME using her right hand. The columns on the left give the results in a graphical way and the columns on the right give the same results in a numerical way. The small dot in each of the squares symbolises the position of the subject. The thick lines are the reference bars. From left to right, the orientation of the reference bar varies from 0°, via 45° and 90° to 135°. The thin lines are the averaged settings (over three trials) of the test bars. The numbers indicate how much the orientation of the test bar deviates (in degrees) from that of the reference bar.

There are a number of important aspects of the results that should be noticed in Figure 3. Firstly, it can be seen that the thin lines within a square are mostly not parallel to the thick line nor parallel to each other. Thus the subject did not respond veridically. This is also evident from the numbers given in the four columns on the right. In this particular example, deviations as large

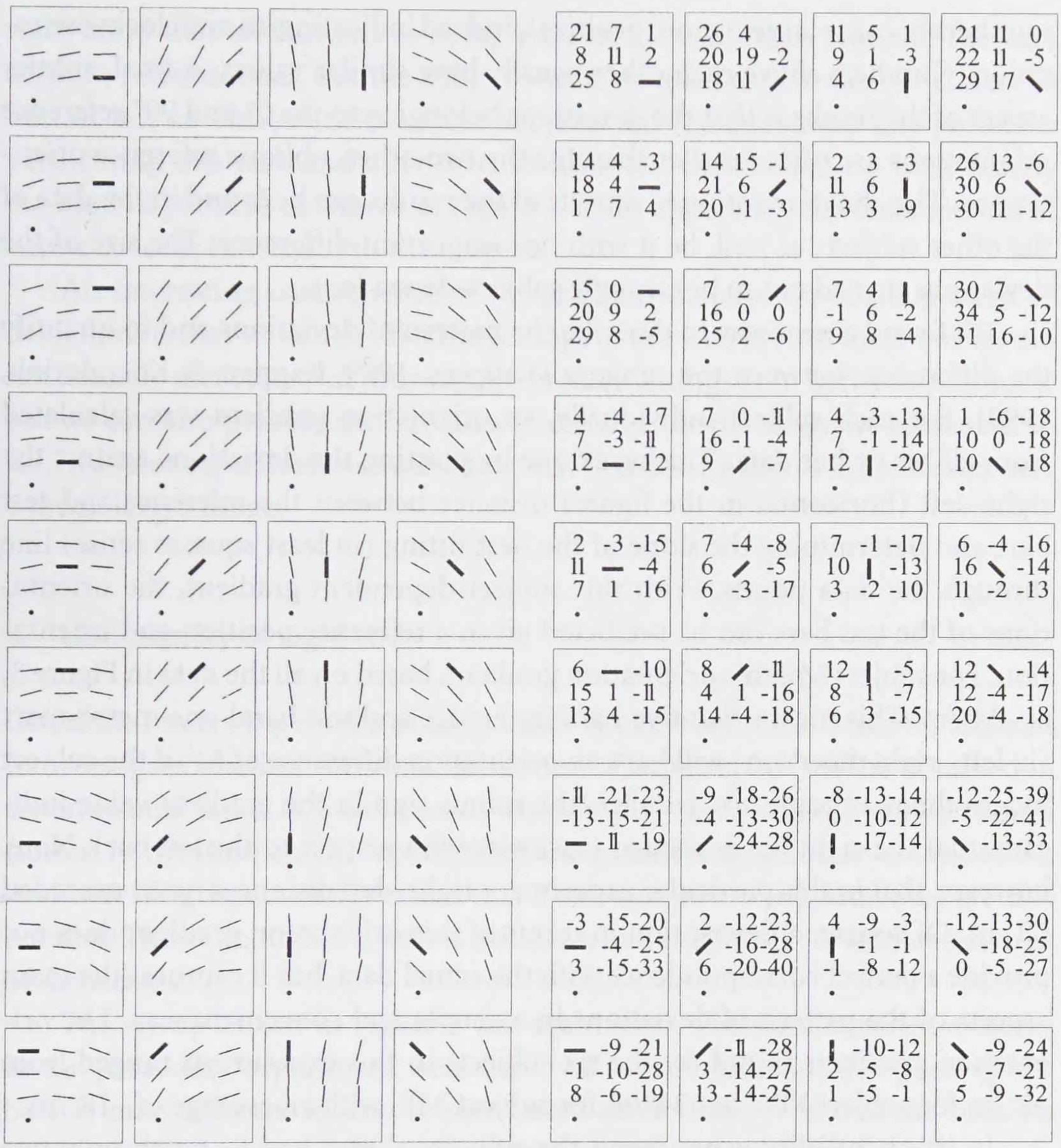

Figure 3. Representative example of results obtained in the parallelity task by subject ME with her right hand. If the subject had responded veridically, all lines within a square would have been parallel and all numbers would have equalled 0.

as –40° occur. The second important aspect of the results is that the deviations are not random but form a distinctive pattern. This can be appreciated best by comparing the orientations of the lines: Going from right to left within a square, the orientations of most of the lines change in anticlockwise direction. On the other hand, comparing three lines vertically above one another within a square usually shows that they are nearly parallel. The same observations follow from the numerical representation of the data: Going from right to left, the

numbers become larger (more positive), indeed indicating an anticlockwise rotation. Numbers above each other usually have similar values. A final, subtler aspect of the results is that the deviations belonging to the 0° and 90° reference orientations are often smaller than for the two other, oblique reference orientations. The above-mentioned aspects of the results can be found in the data of the other subjects as well, be it with one important difference: The size of the deviations turned out to be strongly subject-dependent.

We found a neat way to describe the pattern of deviations and to quantify the differences between the subjects (Kappers, 1999; Kappers & Koenderink, 1999). For each subject individually, an orientation gradient was calculated from all his or her data. This was done by plotting the deviations against the right–left (horizontal in the figure) distance between the reference and test bars and determining the slope of the best fitting (in least squares sense) line through the data points. With this subject-dependent gradient, the orientations of the test bars can be predicted given a reference position and orientation. For subject ME this orientation gradient, based on all the data in Figure 3, is –34°/m. This means that two bars (reference and test bars) one metre apart (in left–right direction) will have an orientation difference of 34° if the subject judges them as haptically parallel (the minus sign in the gradient value indicates that the right bar is rotated clockwise with respect to the left bar). Note, however, that in this particular experiment right–left distances never exceeded 60 cm. Of course, a description in terms of this orientation gradient does not provide a perfect correspondence with the actual data, but it captures the main aspects of the pattern of deviations in a simple and convenient way. The orientation gradients found for the six subjects in this experiment ranged from –2°/m for subject MW to –34°/m for subject ME, with an average of –18°/m.

In this parallelity experiment, the subjects always had to touch only two bars per trial, one of which had a fixed orientation; the other one's orientation had to be adjusted. Displaying the results of all trials in one figure such as in Figure 3, gave the distinctive patterns of deviations. It should be noted, however, that all lines shown in one of the squares were adjusted as feeling parallel to the reference bar. Thus the question remained whether the subject would agree that all the bars as shown would indeed feel as parallel to one another. In other words, is haptic space as consistently deformed as compared to physical space as suggested by the gradient description?

The simplest way to test this research question, was by measuring the full pattern of deviations directly. Instead of only two bars, we put nine bars on the nine rightmost protractors shown in Figure 1. The blindfolded subjects (new naive subjects) were asked to rotate all the bars in such a way with their

right hand that all bars felt as being parallel to each other. None of the bars acted as reference bar, but the subject was instructed to give the bar closest to him or her an oblique orientation. Subjects did not encounter any problems performing this task and after 5 to 15 minutes, they ended up with exactly the kind of patterns as shown in Figure 3. Thus apparently the deformation of haptic space is consistent to the observer.

An interesting consequence of the gradient description of the pattern of deviations is that we can predict the settings of test bars even at locations we did not actually measure. Not only can we predict settings at in between positions, but we can also predict settings at locations outside the range we measured so far. In a later experiment we will show that this description is indeed valid over a much larger range.

3. Collinearity of rigid rods

Given the interesting results of the parallelity experiments, it becomes relevant to investigate whether the same deviations of haptic space will be obtained in other, related tasks. In a collinearity task the subject has to adjust two stimuli (just as in the Blumenfeld experiment) and make them collinear to each other. An interesting aspect of this task is that if two stimuli are collinear, they are also parallel. Thus although the task is different, one might expect similar patterns of deviations.

The set-up shown in Figure 1 was again used. The same nine locations as in the parallelity experiment were used. All 36 combinations for placing two bars at nine different locations were tested three times. Three of the subjects participated here as well. The task of the subjects was to rotate both bars with their right hand in such a way that they felt as lying on the same line, that is, being collinear. Subjects did not receive any feedback on their settings.

In Figure 4 the results of again subject ME are shown. All 36 combinations are shown in a separate square. A graphical representation of the data is shown on the left and a numerical one on the right. Since for each combination of bars there exists a unique physically correct orientation, the deviations could be computed. Clearly, the settings of the subjects are again far from veridical. Note, in this respect, the remarkable resemblance with the pattern of deviations that was observed in Figure 3. Generally, the right bar is rotated in clockwise direction with respect to the left bar. This can also be seen in the numerical representation: The right numbers are mostly negative whereas the left numbers

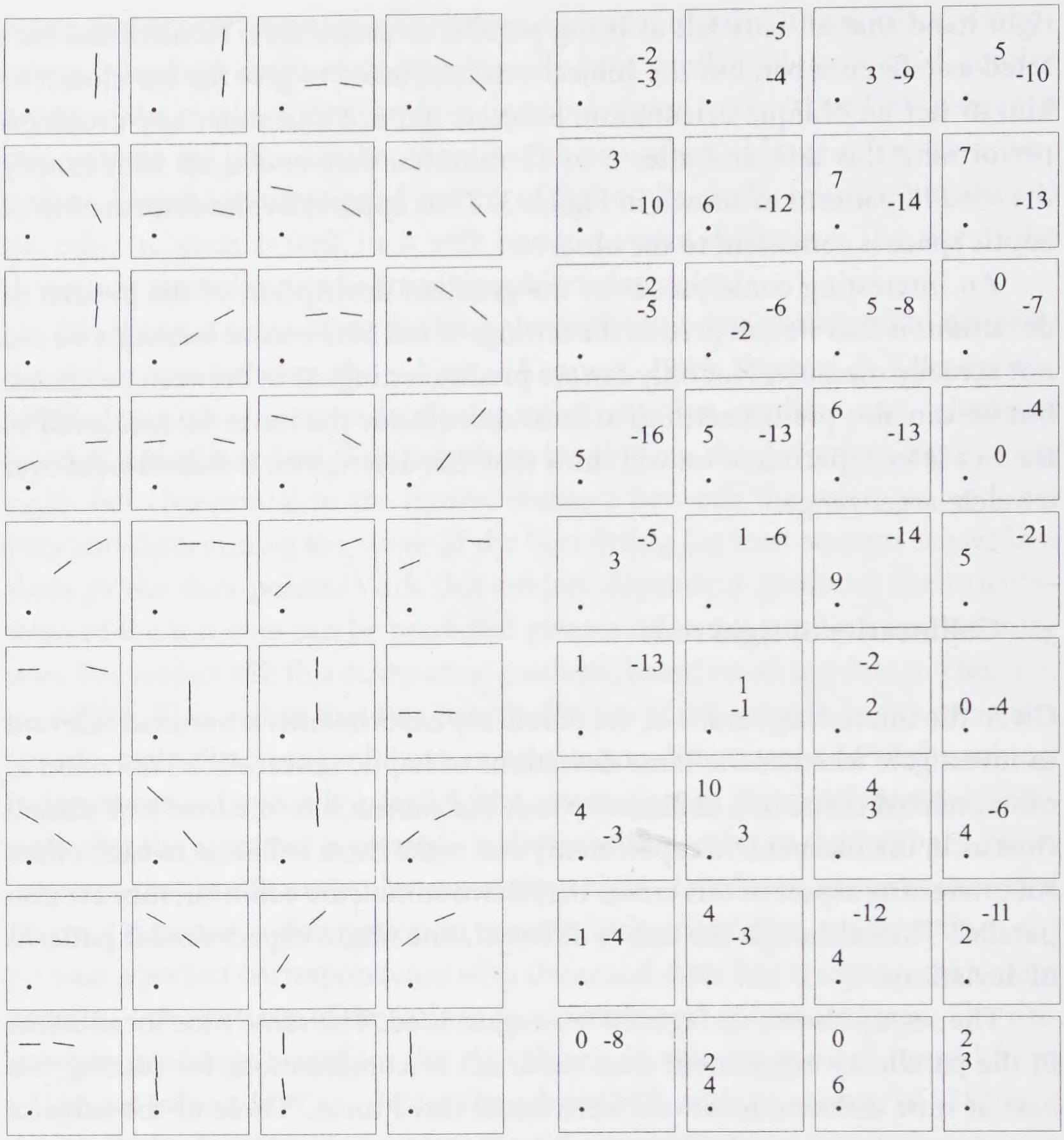

Figure 4. Representative example of results obtained with the collinearity task by ME using her right hand. If she had responded veridically, all lines in a square would have been on an imaginary straight line and all numbers would have been 0.

are mostly positive. The results of the other two subjects are again qualitatively the same but quantitatively different.

Since the patterns of deviations are so similar to those of the parallelity experiment, a description in terms of an orientation gradient was also valid here. For subject ME this resulted in exactly the same value, namely –34°/m. For subjects NK and RR the orientation gradients in the collinearity experiment were –20°/m and –2°/m, respectively (in the parallelity experiment, they

were –22°/m and –7°/m, respectively). Thus these values are very close to those obtained in the parallelity experiment.

4. Pointing rods to targets

A third task we investigated is a pointing task. This task is related to the collinearity task in the sense that the collinearity task can be considered as a double pointing task (both bars have to point towards each other in order to be collinear). Of course, it is not necessary that the observers have considered the collinearity task in such a way. On the basis of the results of the previous two experimental tasks, we expect similar patterns of deviation in the pointing task.

The set-up and the subjects were the same as in the collinearity experiment. One of the bars was replaced by a marker, a circular magnet with a pin fixed to it that fitted in the holes in the centres of the protractors. The blindfolded subjects were asked to rotate the bar in such a way with their right hand that it felt as if the bar pointed in a straight line to the marker. They were allowed to go back and forth between marker and pointer (the bar) as often as they thought necessary. All 72 possible combinations of bar and marker locations were tested three times in random order. The subjects never received any feedback on the accuracy of their settings.

Results of the pointing experiment are shown in Figure 5. For ease of comparison with Figures 3 and 4, once more the results of subject ME were chosen. Although less clear, the settings of the subjects deviate in the same way as was found in the two previous experiments. This can be appreciated best from the bottom row in Figure 5. There, the test bars are on the right side of the marker and most of them are rotated clockwise with respect to veridical (this is also indicated by the fact that most of the numbers are negative). Moreover, the numbers vertically above one another have roughly the same value. The orientation gradients computed from these data sets are –11°/m (for subject ME), –9°/m (for subject NK) and –3°/m (for subject RR). One should double these values before one can compare them to those obtained in the parallelity and collinearity experiments. This can be understood by considering that in the current experiment there is only one bar, which can be misoriented, whereas in the other two experiments two bars play a role. By doubling these values we can see that they lie once again in the same ballpark (albeit that the value obtained for subject ME is relatively small).

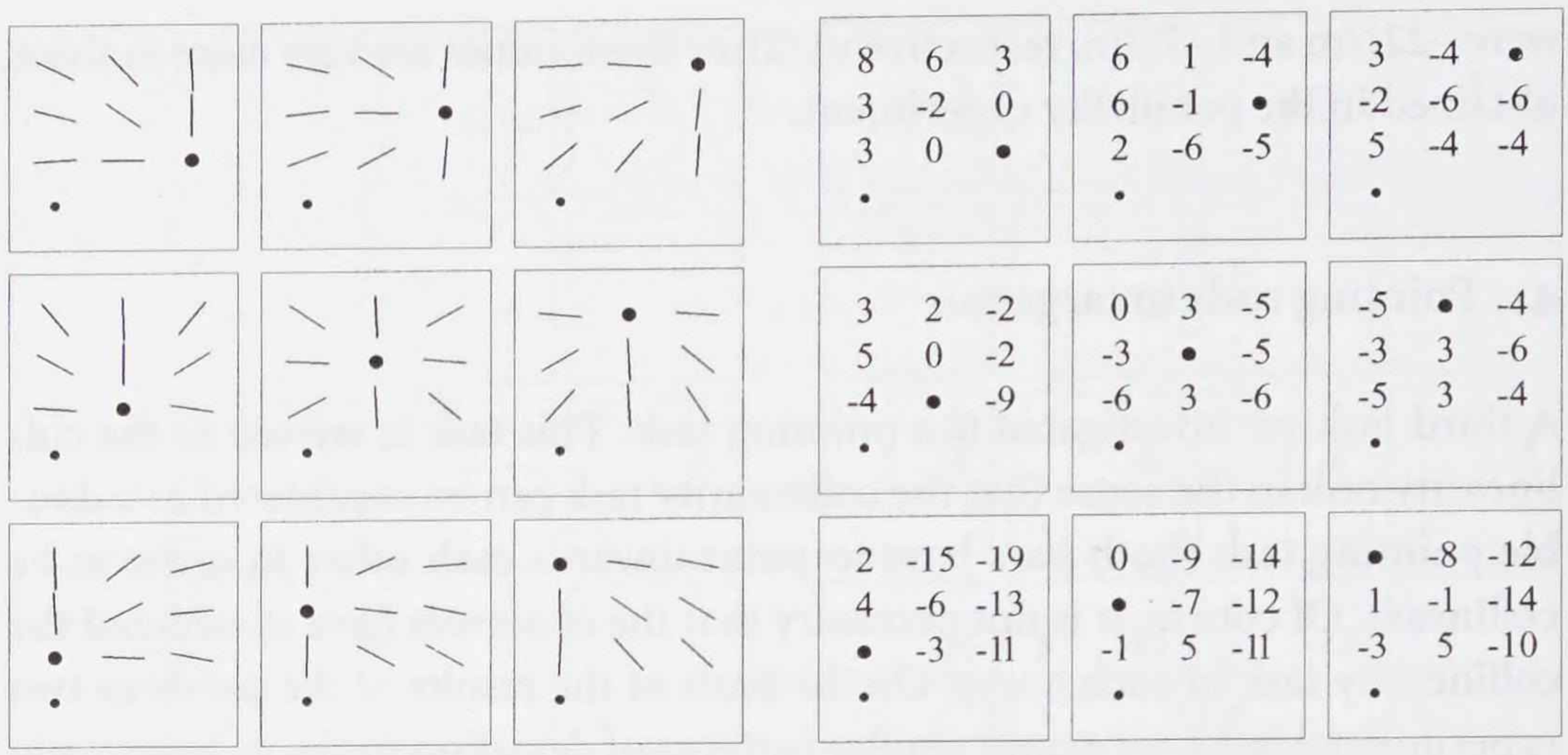

Figure 5. Representative example of results obtained in the pointing experiment by subject ME using her right hand.

5. Bimanual adjustment of parallelity of rods

We had a number of reasons to extend the original parallelity experiment. In the first place we were interested in the question whether the patterns of deviations would continue in the same way if the region tested would be increased. Since we originally used only a part of the set-up shown in Figure 1, this was easy to implement by testing also some of the remaining locations. Another question that intrigued us, was whether the results would remain the same if the experiments were performed bimanually instead of unimanually. An important difference between the unimanual and the bimanual conditions is that in the former situation the subjects have to move continuously back and forth between two locations whereas in the latter case the hands remain more or less stationary at some location. Finally, we hoped to learn more about the difference or the possible similarity between performance with the right and with the left hand. Movements between two locations will in general be quite different for the two hands and involve different muscles. Thus by comparing the results of the two unimanual conditions with each other, and the unimanual conditions with the bimanual condition, we can determine in what way the deformation of haptic space depends on movements.

The experiments were performed in a similar way as the parallelity experiment described previously. Here, different locations for the reference and test bars were chosen, namely the four corner positions and the centre position (protractors numbered 1, 3, 8, 13, and 15 in Figure 1). Subject NK participated

again, as well as two new strongly right-handed subjects. Three conditions were measured, two unimanual ones and a bimanual one. In the unimanual conditions, the procedure was the same as before. Thus the subjects were allowed to go back and forth between the two bars as often as they preferred with, depending on the condition, either the right hand or the left one. In the bimanual condition, the rightmost bar was touched with the right hand while simultaneously the other bar was touched with the left hand. In this condition, subjects were not allowed to move their hands between the two bars, but still they could use as much time as they needed. An example of a subject performing the bimanual task can be seen in Figure 2c. Subjects never received any form of feedback.

In Figure 2d the final setting of the subject in Figure 2c can be seen. It is clear that this setting is far from veridical and that the test bar is actually closer to perpendicular than to parallel to the reference bar. A more extensive set of data is given in Figure 6. These data are collected by subject ML in the bimanual condition. The observations made when discussing Figure 3 can also readily be seen in this figure: Test bars positioned to the right of the reference bar usually deviate in clockwise direction (negative numbers) and those on the left side deviate in anticlockwise direction (positive numbers). Bars vertically above each other in the same box are usually almost parallel. Thus it turned out that again the patterns of deviations could be described efficiently by means of an orientation gradient. The gradients computed for the three subjects in this experiment were rather similar and ranged from –12°/m to –27°/m. Interestingly, for all subjects the gradients belonging to the bimanual condition were always the largest (on average –23°/m), followed by those for the right hand (on average –17°/m) and the left hand (on average –13°/m).

Although in the experiments described so far a number of different subjects participated, we were interested in the distribution of the orientation gradients in a much larger group of observers. Since the original experiments took many hours per subject, we had to design a much more restricted experiment. We decided to limit ourselves to only a few settings per subject. Since the deviations become larger with distance, we choose positions 1 and 13 in Figure 1 for this test. The reference bar's orientations tested were 0°, 45°, 90°, and 135° and all these orientations were presented once at the right (position 1) and once on the left (position 13) of the subject. The blindfolded subjects had to perform the task bimanually. In total 31 subjects participated on a voluntary basis. They were mainly colleagues and students from the Department of Physics.

The results obtained with this large group of inexperienced subjects fitted within the range of results obtained earlier. The average orientation gradient

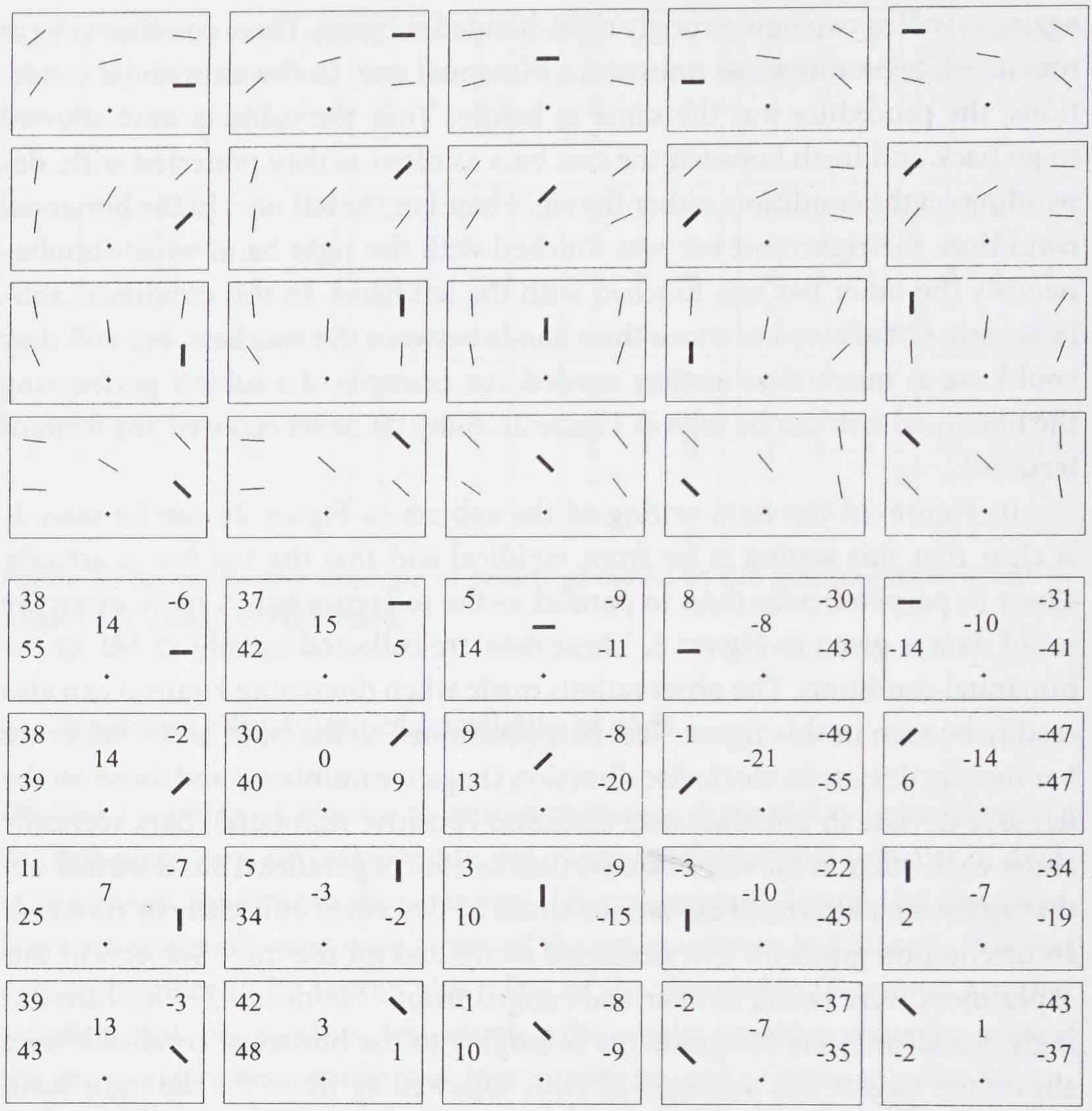

Figure 6. Representative example of results obtained by subject ML when bimanually performing the parallelity task. Note that deviations as large as 55° occur!

was –31°/m and ranged from –12°/m to –58°/m. Thus we could conclude that our findings with respect to the deformation of haptic space have a general validity.

Thus far, we did not find a plausible explanation for the deviations, although it has become clear that they are consistent over all the experimental tasks tested so far. Interestingly, the patterns obtained with the right hand, the left hand and two hands are qualitatively identical. Thus, we can conclude that movement patterns (rotations about the shoulder, rotations about the elbow, etc.) are not the determining factor for the deformation of haptic space. It should be noted, however, that the direction of the deviations is consistent

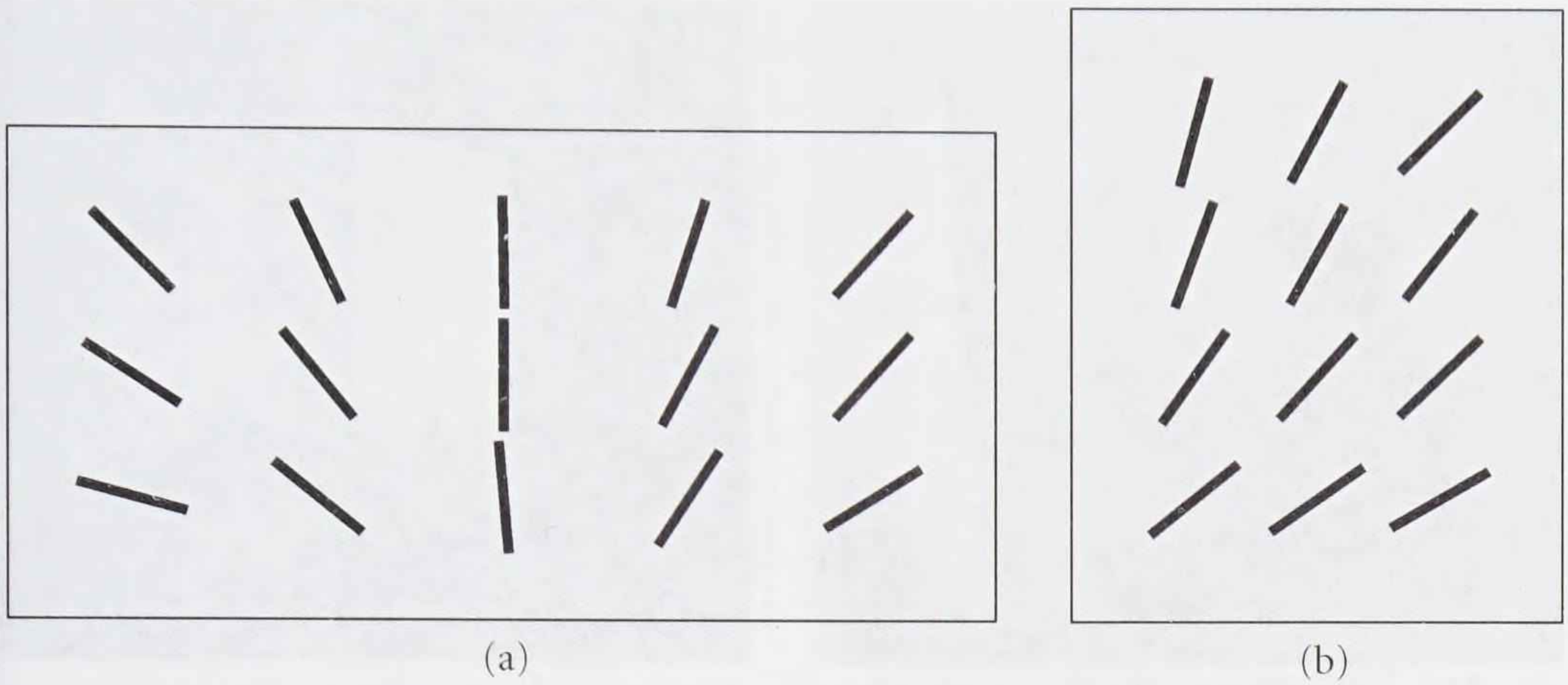

Figure 7. Orientations of the hand (measured along the middle finger) when a subject spontaneously positioned her hand at several positions of the set-up. (a) Results for the table plane set-up. (b) Results for the set-up in the midsagittal plane.

with the way the hand rotates when moving from one position to another. This is illustrated in Figure 7a, where the orientations of a subject's hand (measured along the middle finger) are plotted for the various positions of the set-up when the hand was spontaneously positioned. If, for example, the hand moves from position 7 to position 3 (see Figures 1 and 7), the hand orientation changes in a clockwise fashion. This is true for both the right and the left hand. Similarly, the setting of the test bar at location 3 deviates in clockwise direction, but not nearly as much as the orientation of the hand changes. Consequently, it is tempting to hypothesise that at least the direction of the deviations is determined by the movement restrictions of the hand and arm.

6. Parallelity of rods in the midsagittal plane

So far all the experiments took place on a table plane. The hypothesis mentioned above can be tested most easily by doing the experiments in another plane and investigating whether the deviations are again in a direction that coincides with the orientation changes the hand undergoes when moving from one position to the next. One obvious plane for such an experiment is the midsagittal plane (a frontoparallel plane would have been another obvious choice). When moving downwards over a midsagittal plane, the right hand changes orientation in clockwise direction. Similarly, when moving backwards the right hand also rotates clockwise. This pattern is illustrated in Figure 7b. If our hy-

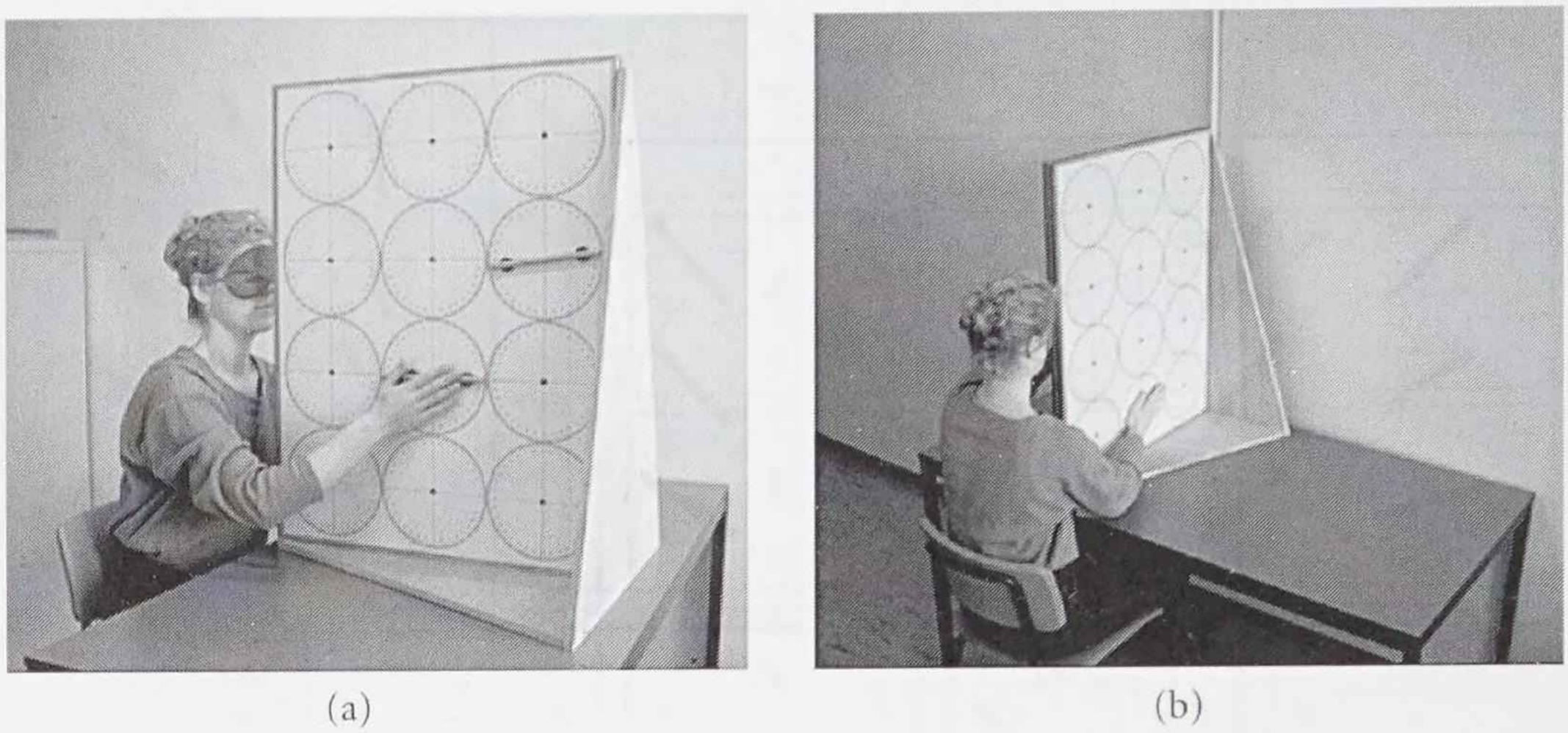

Figure 8. Two photographs of the experimental set-up in the midsagittal plane. (a) A blindfolded subject performs the parallelity task unimanually with her right hand. (b) The same subject performing the parallelity task bimanually.

pothesis is true, the pattern of deviations found on the midsagittal plane should look like a scaled version of Figure 7b (that is, the deviations will be smaller but in the same direction). This will be tested in the following experiment.

Photographs of the set-up used for the experiments in the midsagittal plane can be seen in Figure 8. On both left and right sides of this set-up protractors are printed. For the present experiments, on each side four locations are used for the reference and test bars. In this way we measured the maximally available range in the midsagittal plane. Four conditions were measured, two unimanual ones and two bimanual ones. An example of unimanually performing the parallelity task, in this case with the right hand, is shown in Figure 8a. Both reference and test bars are located at the same side of the set-up, and that could be either the right or the left side. The subject has to move back and forth between the two bars. In Figure 8b, an example of one of the bimanual tasks can be seen. Here the reference bar is on the right side and the test bar (not visible) is on the left side. The reverse condition (reference bar on the left and test bar on the right) was also measured. Three strongly right-handed subjects participated, one of whom (NK) also participated in all of the previous experiments.

In Figure 9 an example of the results of subject NK obtained in one of bimanual conditions is shown. Here the reference bar was located at the left side of the set-up and the test bar at the right side. The subject was seated at the left side of each square. All lines indicate the orientations of test bars averaged over three trials. From top to bottom row, the reference orientations were 0°,

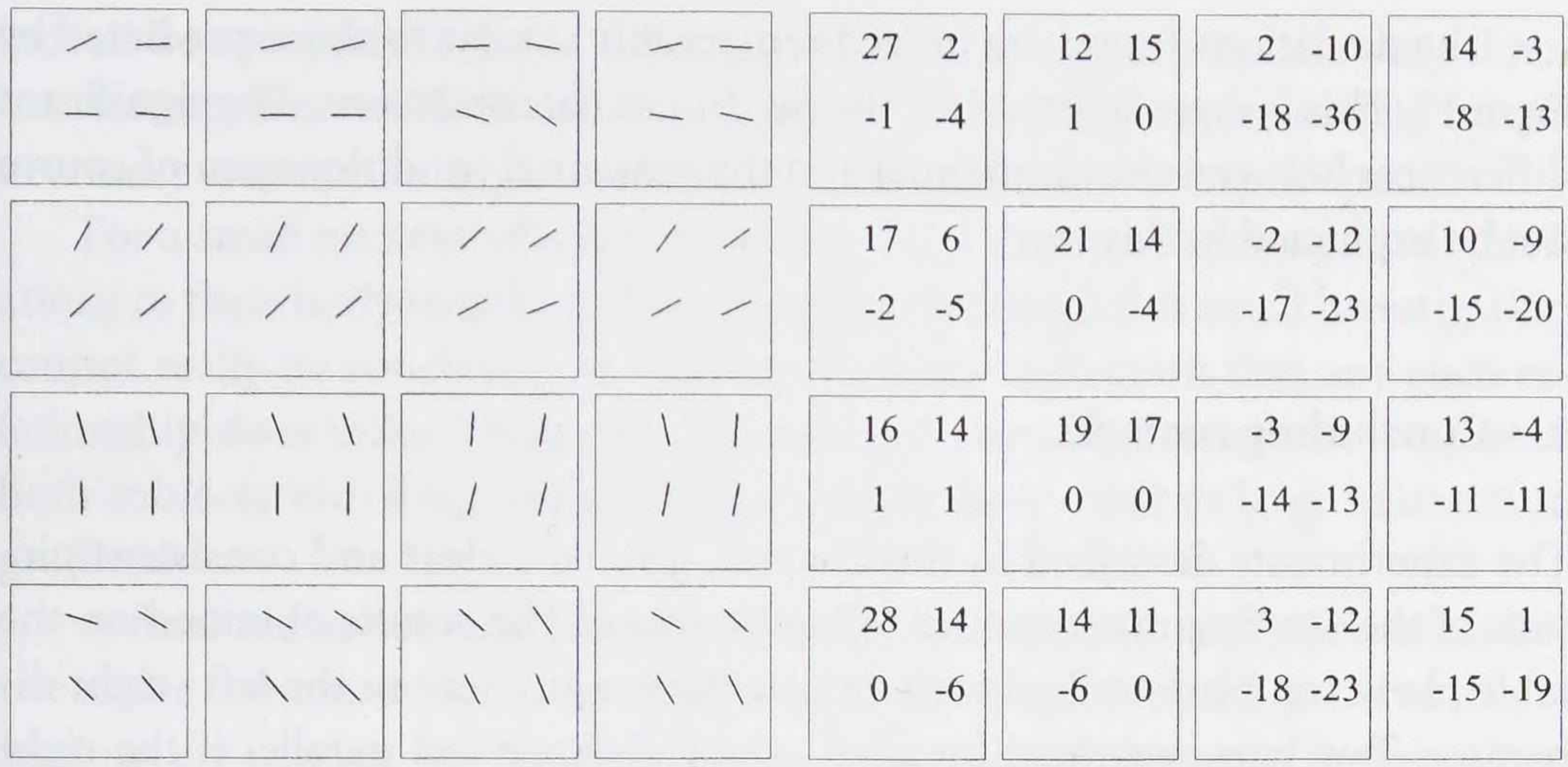

Figure 9. Representative example of results obtained by subject NK in one of the bimanual conditions in the midsagittal plane. The reference bar was located at the left side of the set-up and the test bar at the right side.

45°, 90°, and 135°, respectively. In the first and fifth columns, the reference bar location was the lower left position, in columns two and six, the lower right, in columns three and seven, the upper left, and finally in columns four and eight the upper right. It can again clearly be observed that the responses of the subject are not veridical. The deviations of the other two subjects are similar in size and direction. Since a gradient description was rather successful in the previous cases, we computed for all subjects and all conditions gradients in both the forward-backward and the up-down direction. For all subjects and all conditions, the gradient in the up-down direction was positive and significantly different from zero. This means that going upwards involves a rotation in the anticlockwise direction. Remarkably, the gradients for the bimanual conditions were significantly larger than those for the unimanual conditions, namely 36°/m versus 8°/m (averaged over subjects and conditions). The gradients in the forward-backward direction were significantly different from zero for subjects in the bimanual conditions (on average 14°/m), but non-significant for all the unimanual conditions. One should note, however, that two significant gradients in perpendicular directions, actually are identical to one gradient in an in between direction. Since the gradients in the up-down direction are much larger than in the forward-backward direction, the average gradient direction has to be rather close to the up-down direction (in fact, the average gradient axis deviates 21° from the up-down direction).

The deviations found are indeed remarkably similar to those predicted by Figure 7. This is especially true for the two bimanual conditions. The significant differences between the unimanual and the bimanual conditions can of course not be explained in this way.

7. Concluding remarks

The experiments described in this chapter, give us a clear and consistent picture of the continuous structure of haptic space. The results obtained on the table plane can be described with an orientation gradient in the left–right direction: Two bars separated by a left–right distance feel parallel if the right bar is rotated clockwise with respect to the left one. The amount of rotation needed depends linearly on the distance. The distance the two bars have in the forward-backward direction is not of any influence. The results obtained in the midsagittal plane are similar: Here the orientation gradient lies along the up-down direction whereas again the distance along the forward-backward direction is not of influence. This latter finding is only true for the unimanual conditions because in the bimanual conditions there is also a significant gradient in the forward-backward direction.

Interestingly, the deformations are distinctly in the direction one would expect if the difference between spontaneous orientations of the hand at any two given positions would determine the result, but the actual deviations are much smaller (a rough estimation shows a factor of three to four) and closer to veridical. Apparently, subjects compensate in a consistent way for the fact that the orientation of their hand changes when moved from left to right or from top to bottom, but not in a completely sufficient manner. It should be stressed that this "compensation" is done fully unconsciously, because subjects certainly feel their final setting of the test bar as being parallel to the reference bar (or, depending on the experiment, collinear or correctly pointing); neither the veridical orientation nor the orientation predicted by the hand orientation is haptically perceived as being parallel!

We did not yet investigate this "compensation factor" in a systematic way, but it is certainly appealing to explore whether a fixed relationship exists between the orientation gradients and the gradients in hand orientation. Equally of interest, is the possible and probable relationship between the orientation gradients in the various directions and on the various planes. Such questions can only be answered by running a relatively large number of subjects in the various conditions of the experiments, so that the orientation gradients can

indeed be compared directly. Unfortunately, such experiments are very time-consuming, but even so it will be a challenge for the near future as they form a necessary step on the way to a three-dimensional model of haptic space.

For a small number of subjects we have tried to relate the size of their deviations to their body lengths and arm lengths. Although this small investigation cannot really be conclusive, we did not find any indication that any such relationship does indeed exist. We did not find any systematic variation, since both subjects with long and short arms, could have small or large orientation gradients.

A final remark should be made about the similarities and differences between the unimanual and bimanual conditions. In general, the patterns of deviations are similar, but the deviations are significantly larger in the bimanual cases. Apparently, the seeming advantage of the bimanual conditions that the two bars can be compared simultaneously is more than cancelled out by the fact that the comparison involves different hands. Appelle and Countryman (1986) report similar findings in a matching experiment where in both the unimanual and bimanual conditions the stimuli had to be touched successively. However, in this context, we think that the finding that both unimanual and bimanual spaces can be described by a similar gradient is of more importance than their difference in size, since such an outcome could not be predicted in advance and thus is not at all trivial.

In conclusion, from all the experiments a very consistent pattern of results emerges: Haptic spatial relations are reproducible, haptic space is clearly deformed with respect to Euclidean or physical space, haptic space has a certain continuous structure, and this structure can be described efficiently by means of subject-dependent orientation gradients. This is true for both planes measured, namely the horizontal table plane and a midsagittal plane. Finally, haptic space appears to be qualitatively but not quantitatively similar for the unimanual and bimanual conditions.

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CHAPTER 7

Touch and the observer's vantage point

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That the observer has a vantage point in vision is obvious. But in many ways the observer can be deemed to have a vantage point in touch too.

1. Touch and the observer's vantage point

On a clear day, when you seem to see forever, as you stand spellbound before a vista of distant mountains, you have an impression of space, but you also have a well-defined vantage point. The vista specifies your own unique location (Gibson, 1979). If you take a photo that day, the photo tells where you were standing. It says you were "here!" The contours of the hills not only reveal where they are, silhouetted against the sky, they also indicate the special spot from which the photo was taken. If you are on a mountain track above Salzburg, and you move to one side, to take more pictures, the shapes of the brows of the hills around Salzburg will change slightly to specify your trajectory. Parts of distant hills bearing a fortress evident in one picture may be hidden in a shot from a neighbouring viewpoint along the track. If the vista opens out to the great plain in one direction, you may see as far as the horizon.

Visually, the dimension of distance is anchored at one end by the distal object. The other anchor is the observer's vantage point: no vantage point, no distance. Acting as a far target for observation, the horizon is often one end of the of the distance continuum. It is a visual limit for a terrestrial plain. The other end is the observer's vantage point. It is the origin for measures of the distance of the target from the eye. This origin is the centre of a sphere of directions. From the origin we can move our gaze in six ways. We can redirect our heading via yaw, pitch and roll, and we can move our origin up, sideways and forward. That is, not only do we have to look into space from our own limited standpoint, we also have to gaze in a particular direction at any given moment. We look up (changing pitch) to the heavens above the horizon, or down to the

ground. We can look left or right (yaw) to where our path may take us, perhaps along a cliff edge of a plateau. We can also revolve gymnastically to stand on our head (roll)! Also, our origin can be moved left and right along the path as if on a moving belt, be raised or lowered as if on an elevator, or tempt fate by allowing itself to go to the front and towards the edge of the bluffs to be borne aloft on a paraglider or to the back and safely away from the precipice, perhaps to fix our straps. Evidently, there are three ways to change our direction of gaze from a fixed origin, and three ways to move the origin: Six degrees of freedom for our singular vantage point.

2. In touch as in vision?

The observer's vantage point is evident in vision and it is made known precisely and exactly in pictures based on optic projection (Hopkins, 1998). It has six degrees of freedom we take liberties with daily. Is there anything like the eye's vantage point in touch? Or does touch depend entirely on direct contact, that is on stimuli in proximity to the body? Does touch rely so much on proximal arrays that it resists any use of a well-defined vantage point (a question discussed insightfully by Hopkins, 2000, in prep.)? Is there any way in which touch enquires about distant objects, far removed from the observer, not abutting the body (on which see able speculation by Lopes, 1997)? In what ways might touch act as a distal sense as well as a proximal sense? Does touch have degrees of freedom? Does it use contours of objects, like the brows of hills, to specify its location? How might a change in tactual location be reflected in a tactual vantage point? Which of the six changes can we cope with most readily? Any that do not involve complex combinations, inversion or left–right coordination? By way of limits, is there a tactual sky and horizon, like the visual paraglider's high above Salzburg?

Visual impressions of a distinct, precise vantage point are well matched by the photos we take of the attractive vista. The photo is a record of the light rays coming to a single point, through a lens. If we made pictures for touch, using displays with raised elements (Edman, 1992) would touch provide us with information about a particular vantage point? Some might think the pictures would do so only for the sighted, who can imagine what the tactile display could look like, and interpret the picture bearing in mind a visual vantage point (Revesz, 1950; Hopkins, 2000). Surely there would be a lot to learn about vantage points if a blind person unfamiliar with pictures were able to use a picture drawn from a single vantage point (Lopes, 1997).

I will discuss the questions here in an argument about the distance continuum in touch. Fundamentally, I will propose that vantage points abound in touch. Touch deals with directions from points, especially distance in the forward direction, though it has some trouble (like vision) with inversion, and it is prone to left–right errors. And I will contend vantage points can be used usefully in tactile pictures, and often be interpretable through touch in similar ways by the sighted and the blind (Heller, Kennedy and Joyner, 1995; Heller, Calcaterra, Tyler and Burson, 1996).

Let us begin with a crucial thought experiment. Imagine touching or looking at a line of raised dots (Arnheim, 1974; Kennedy, 1993, 1997, 2000; Holmes et al., 1998). The dots are elements that induce a perceived line. The perceived line crosses the empty space between the dots. Much of our perception of space is like this. We see or touch a few objects on a surface and gain an impression of the relations between them. We also get an impression of the relations between the inducers, the induced line and our own vantage point. The vagaries of these relations are the topic to be discussed here.

3. The historical legacy: Molyneux's question and Murphy's Law

Many scholars have asked about the relation between vision and touch. Vision's vantage point was often plain, and often mistakenly assumed to be entirely obvious, in these discussions. Alas, the idea that touch might have use for vantage points was often conspicuously absent. The result was, I think, a very lop-sided debate (Kennedy and Merkas, 2000).

William Molyneux , an Irish barrister of the late seventeenth century, had a wife who was blind. He was moved to throw a celebrated question into the pool of philosophical puzzles. Query: would a blind person familiar with cubes and spheres be able to recognize them if given sight by some enterprising operation? Many eminent scholars who did not know the answer rushed to reply. The character of their arguments set the tone of enquiry for many years, with vision given abilities explicitly, and touch belittled by errors of omission. In a variation of Murphy's Law that what can go wrong will, parallels that might be misconstrued were.

John Locke (1690, see also Boring, 1942, 1950) in an "Essay Concerning Human Understanding" commented that vision gives us more than light and colours. He said it also gives us the far different ideas of space, figures and motion. Locke discussed projection to a vantage point. He noted that a sphere

is projected in vision as a circle and a cube as a square or hexagon. He described these projections in terms of vision. He did not consider projection in touch.

Reid (in 1764, see Boring, 1942, 1950; Hopkins, 1998; 2000; in press) astutely described how vision sees changeable aspects of an object in its projections. But in touch, he thought, we gain the impression that all these objects are identical. Vision, Reid wrote, initially takes a sphere as a circular form, variously coloured if it is partly in light and partly in shadow. But the genius of perceptual learning is that aided by touch we can discover that different distances are relevant, not just various colourings, and "this perception" gives the circular form convexity, adding a third dimension (VI, Section 23).

Synge (in 1693, see Eriksson, 1998) debated the basis for Molyneux's question, asking what a person born blind might have as an idea of a sphere or a cube. A tactile idea of a sphere, Synge proposed, was of an object that felt the same all over. In contrast, a cube has distinct parts. Some are sharp vertices, some are flat, and some are long straight corners between flat areas.

Berkeley (in 1709, see Eriksson, 1998) noted when we look at a point, the point will not tell us whether it comes from a short distance or a long distance. Its distance is indeterminate.

Locke, Reid, Synge and Berkeley do not offer systematic conjectures about touch having vantage points, dealing with projections and anchoring distance information. Locke's spheres and cubes project shapes in vision, and not in touch. But the direction of parts of objects vary just as much in touch as they do in vision. Reid failed to capitalize on the fact that cubes have different aspects to touch. Synge's spheres always feel the same. He does not sufficiently realize there are many ways one might vary the vantage points from which the contact is made. When Synge makes the point about distinct parts of a cube, one wants in vain to have an orderly treatment of the fact that some of the parts of the cube could be near and others far. Berkeley's visual point on our retina could be compared usefully to a tactile point on our skin. The visual point does not tell us how far it's straight-line transmission has come. That requires a specific informative context for the point (Gibson, 1979). The tactile point does not tell us how long a rod is behind it. Wielding a rod does tell us about its length (Turvey, 1995).

Diderot (in 1749, see Morgan 1977), French encyclopedist, is a radical in this company of British Empiricists. Ironically, he offered more empirical observations than the Empiricists. His observations make notions of a tactile vantage point relevant. He discussed the abilities of two blind men – a man from Puiseau, and a mathematician from Cambridge. Both of these men dealt with shape and distance. They appreciated that we reach out for objects from wher-

ever we are standing. The man from Puiseau spoke of reaching out with his stick. Sometimes an obstacle might block his access to the object he was trying to touch with his stick. The outcome is a valid awareness of spatial properties, the body as origin, several objects around it, some near and some far, an outstretched arm, extended by a stick, and occlusion of one object by another. This kind of awareness of occluding boundaries allowed the blind man of Puiseau to draw profiles of objects. Hopkins (2000, in press) describes this kind of awareness as beliefs about objects. But likely the awareness of occlusion and our vantage point can be much more than a belief. That is, some arrangements of touchable objects give rise to percepts. Also, some implications of arrangements of dots and objects are perceived, not just believed. We perceive linear arrangements of dots, and we may perceive directions. Further, surely we may shift from using one vantage point (say our left hand's location) to using another (say our right hand's) and have perceptual effects as marked as a Necker Cube's reversal. One part of an object may face our left hand, but its back may be near our other hand, we perceive. The important issue here is the conditions that produce shifts that are largely perceptual and the ones that largely affect beliefs. There is likely no need to deny one or other kind of condition.

Is there indeed direction in touch? A static stick may not imply a direction, but, as Diderot mentioned, a motion is inevitably in a particular direction (and we can if we wish take the stick to be pointing in a particular direction). What about shape? Our hands pass through a succession of places, in following a string, Diderot wrote, so if the string is taut, it provides a succession of points or places that can be combined, using memory, into a straight line. If it is slack, the combination will result in a curve. We can recall the shapes and refer to the properties we discover through touch, across a succession of points, he conjectured.

Diderot's discussion lead him into fierce contradictions. We combine tactile points, using memory, and can later refer to the products, Diderot believed. But he went on to argue that touch would not allow us to imagine figures. Are reference and imagining (or pointing) different? Diderot argued that to imagine figures we have to separate the lines or borders of shapes from their background, and this requires the lines or borders of figures to be defined by different colours than the background. This is clearly silly. We can imagine raised lines, not just coloured lines. In both vision and touch, we perceive continuous lines induced by rows of dots. The spaces between the dots have no specific colour or height. The perceived lines too have no colour or height, just pure continuity. We can combine the dots, use memory, and later refer to the result,

but not imagine what we have done? Tut-tut! Imagining and referring seem suspiciously like the same operation by two names.

There are chicken-and-egg problems in Diderot. What enables us to know that a set of points is in a straight line? The line itself cannot tell us, without some ado, because we could be suffering an illusion (Heller and Joyner, 1993; Millar, 2000). Evidently there is an empirical question here: What is taken to be straight and crooked in touch? We cannot just assert straight or aligned things perforce are perceived as straight or collinear or aligned (Cabe et al., in prep.; Kappers and Koenderink, 1999).

Let us take away from Diderot one valuable idea: touch involves reaching in a direction, and so we have at least one kind of vantage point in touch.

Running counter to his own restrictions on imagination, Diderot noted that a blind man could consider a sphere, and then envisage a smaller or larger object, with the same shape. Change of scale leaves shape invariant. In this fashion, the blind man could imagine the terrestrial globe. Atoms and molecules can be imagined in the same fashion. But further, surely the blind man can imagine where atoms or celestial spheres are in direction from us: in front of us or to one side, near or far, at small distances or huge ones. That is, direction in touch implies a wide range of distances both perceptually and cognitively, it is likely.

The idea that touch supports implied relations between objects and ourselves deserves a great deal of attention. Just as touch's basis for perceiving truly straight things needs to be explored, so too our consideration of possible vantage points, some real and some imaginary, cannot be taken for granted. Just as there are explicit numbers, numbers that are implied, numbers that are real and numbers that are imaginary, so too touch may serve an observer entertaining many kinds of vantage points, some really occupied by our body, or by objects we are or have been touching, and some imaginary. Since we reach out in certain directions deliberately, we obviously have targets before we reach, and the targets have imagined or perceived directions. Since we can intend to move our vantage point to pick up objects that are just out of reach at the moment, we can also imagine moving our vantage point.

What about the relations between two directions? It is these angles that give us perspective, let us note. Descartes (in 1638, see Boring, 1942) came close to posing systematic parallels between vision and touch in their use of perspective, and his conjectures may have influenced Diderot writing about a blind man reaching out with a stick. Descartes explained that in visual fixation our two eyes converge on a target (Cabe et al., in preparation). The directions the two eyes are gazing are like two rods crossing at the target (Boring, 1942).

If we can look from two directions in a fashion that is like using two sticks, and gain perspective on an object's location and distance, surely we can reach with sticks in two directions and gain similar knowledge. Descartes described a blind man holding two sticks that intersect a short distance in front of him. Descartes suggested the man could estimate the distance to the crossing-point. The estimate would be made using a kind of natural geometry, Descartes believed, based on the angles of the hands, wrists and arms, and similar effects would arise in visual convergence. In fact, vision is poor at using convergence angles, Gogel (1961) concludes. However, Cabe et al. (in preparation) report touch is quite good at estimating the distance to the intersection of two hand-held sticks. The pairs of sticks Cabe et al. tested were positioned one to the left of the median plane, one to the right. Distances of intersections in front were estimated much more accurately than ones to the left or right sides (as in Kappers and Koenderink, 1999), which were underestimated more as the intersection departed from straight ahead (possibly because the angle of intersection diminished considerably to left and right, and when it was tiny it was overestimated).

4. Tactile pictures: Eriksson's history

Eriksson (1998) argues that the discussion of the relation between vision and touch from the Seventeenth century onwards likely influenced many educators of the blind. She has written about the manufacture of tactile displays for the blind from 1784 to 1940. Many of these displays were pictures in raised form, using solid lines, or dotted lines, or bas-reliefs. In the writings of the pedagogues that Eriksson surveyed, ideas about touch as a spatial sense are evident. But once again the claims about touch only envisage quite modest and highly imperfect parallels with vision.

Like Diderot and Locke, educators in France, Germany and Britain stressed that motion was needed for tactile perception of shape, size and distance. Consider a few discussed by Eriksson. In France, in the early Nineteenth century, Guillié noted the blind could only have successive ideas of the objects they touch. But then he added that they can perform a secondary task, to bring these impressions together, and perhaps a third task in order to compare impressions. In Britain, in the middle of the Nineteenth century, Fowler discussed passing our fingers over a table slowly or quickly. The rate of motion and the time taken indicate the size of the table. We only need a few contacts to get the impression of a continuous table surface. In Germany, at the turn of the cen-

tury, Heller wrote that the mobility of the hand is a key condition for the development of the blind person's sense of direction. He wrote about blind pupils examining tactile displays using active exploration (Philbeck et al., 2001). He also described a subject imagining an index finger moving from one point on a tactile display to another. But Heller then argued that it would be in vain to try to form a total impression of a large object close to us via touch. To form just such an impression we have to remove the object to a larger distance, mentally, and somehow reduce it, he avered. Going to extremes, he then hypothesized it is impossible to get a simultaneous impression from a large object – only a small object will permit this in touch.

Eriksson found tactile displays made by Martin Kunz (1847–1923) in institutes for the blind throughout Europe and North America. Kunz not only made many displays, he theorized about the abilities they called on. In one extraordinary conjecture, he claimed blind people often do not have a sense of distance. He argued the sense of distance does not develop if one becomes blind, notes Eriksson (1998, p. 77). In a curious turn of events, Kunz proposed that paradoxically the blind could have a well-developed sense of location, indicating the places of many objects, but this was by no means the same as a sense of distance.

The teachers who worked with the blind, and the manufacturers and designers who prepared tactile pictures, were likely deeply influenced by the debates among philosophers and education theorists. Gall (in 1837, cited in Eriksson, p. 92), a Scottish clergyman who prepared tactile pictures, wrote "The Blind can feel the shape of any image they can handle; but not having any idea of perspective, it is only an outline which can be perceived". Later, in the century Martin Kunz, discussing tactile pictures, wrote that for the finger there is no perspective, Eriksson reports.

Perspective and directions from the observer's vantage point are often at issue, but in disjointed ways, in the instructions accompanying pictures for the blind. Consider the caption for a picture of hot-air balloons in a picture book for the blind, published by the National Institute for the Blind, London, in the 1920s. Eriksson (pp. 127–128) quotes the caption: "Imagine the rectangular border represents an open window .... Inside the border represents open space ... Stretch out your arm through the window ... and move it about in every direction .... If you could stretch out your arm till it was five or six hundred yards long, you would be able to touch the nearest balloon ... a second balloon is shown .... It is really the same size as the first, but being much further away it has the appearance of being smaller and fainter ...." (I have abbreviated the caption.)

Directions from the observer's vantage point are adumbrated usefully in this caption. But inconsistent use of spatial terms obscures the lesson. The caption tells us that a balloon lies in a certain direction. But then it alters its set of key terms. It does not spell out what aspects of direction are relevant. It changes its terms to appearance, size and faintness. In terms from Lopes (1997, p. 438), having "identified the picture surface with the visual field," the use of the significant term direction is over-ridden. The caption could have said the direction of the top of the nearby balloon is close to the direction of the top of the window frame. It could have added that the direction of the basket at the bottom of the balloon is close to the direction of the bottom of the window frame. There are only slight differences in direction so the nearby balloon almost fills the window frame. The directions to the top and bottom of the frame, it could have said, are only slightly wider apart than the directions to the top of the nearby balloon and the basket. Then, the caption could have added, the more distant balloon has a much small difference in direction between its top and its basket. It could have pointed out that as a balloon recedes the difference between the directions of top and bottom has to diminish steadily.

It is distinctly odd that most theories of touch argue spatial touch requires motion in particular directions, in straight and curved paths, and stress that otherwise we have little except pressure in the finger and the resistance of surfaces, but then draw in their horns when talking about pictures. Often, theory of touch in concert with pictures describes "fingers", and fails to entertain motion, direction, mobility, and any of the other degrees of freedom that give spatial touch its flexible modus vivendi and its information (Lopes, 1997; Hopkins, 2000, in press). Theorists opine that the blind can touch ordinary surfaces and imagine directions. They do not go on to say that blind people touching a picture surface could take some picture elements as telling us about directions from a vantage point. The result is interminably one-sided discussions.

Lopes (1997) argues that the proper conclusion "to draw here is that perspectival perception is not unique to vision. It is part of any conception of space that enables us to move around our environment, and will be present in experiences in any sense modality that represents space. If perspective is spatial and not distinctively visual, then the argument that vision differs from touch because a component of its content is perspectival, characterized as shapes and sizes on a visual field, is unsound" (p. 437). He adds that we have made a mistake in interpreting vision as like a picture, and a picture as solely visual. We redoubled the error in interpreting images in the head as like pictures, and therefore as like vision. He continues "The error is compounded when, having postulated pictures in the head, we then explain pictures on the canvas by means of

their alleged similarity to those postulated mental pictures." (p. 439). See also allied arguments from Costall (1990), and Cutting and Massironi (1998).

5. Recent evidence

The history of thought on touch, the blind and space is full of unfortunate assumptions it seems. But there is no a priori reason to insist touch is a non-spatial medium. Motion around an environment could well give a blind person an astute awareness of the relative distances between points, and their directions with respect to each other and the observer.

In practice, how well do blind subjects know the relative distances between parts of a room? Here I will describe some of the key studies of the past decade. For an analysis of studies that paved the way to these reports see Millar (1994, 1997, 2000), Kennedy (1993) and Kennedy, Gabias and Heller (1992).

Haber, Haber, Levin and Hollyfield (1993) tested 7 blind, highly mobile adults (two of whom were congenitally blind) estimating the absolute distances between 10 objects in a familiar room. The subject sat at one location in the room, surrounded by the target objects, to make the estimates. The estimates were all closely correlated to actual distance, regression analyses showed (all correlations within the range .84 to .99). There were no differences between early-blind and late-blind subjects. The two-dimensional map of distances and locations one could draw using the subjects' estimates closely matched the actual room, as an 88% scale model. There was a single zero point for the estimates – the observer's vantage point.

Haber et al. compared the distance estimates of the blind to estimates made by sighted subjects in the same room. The sighted subjects were familiar with the room. They found no significant differences between the estimates of the blind and the sighted, except that the sighted underestimated the distances slightly less (5%) than the blind (12%). Haber et al asked how minor variations in the origin or zero point for the blind compared to similar minor variations in the sighted. They found no significant differences.

Instructively, Haber et al. asked the sighted and the blind subjects about the 10 objects in a second condition. In this second condition, the subjects sat in a second room, and were asked about the remote room. The results were the same for both the sighted and the blind: the original, now remote room space was reported as if it had shrunk by 30%!

Haber et al. were not sure of the reasons for the underestimations of distances, but whatever factors were involved they may be similar in the blind and

the sighted. The major findings are the accuracy of the estimates and their close correlations with actual variations in distance.

Haber et al. compared the estimates of distances between pairs of objects that could be joined without intervening barriers, and pairs of objects that had intervening barriers. There were no significant differences between these distinct pairs, for either the blind or the sighted. Evidently, occlusion that requires a detour in travelling between objects did not impair distance judgments in the blind.

Haber et al.'s results are similar to those from Loomis et al. (1993), comparing sighted and blind adults on spatial navigation tasks. Landau, Spelke and Gleitman (1984, see also Landau and Gleitman, 1985; Landau, 1991) tested blind children on their ability to find their way from one object to another in a room. They reported that if a preschool child learns about four objects A, B, C and D, by walking from A to B to C to D, thereafter the child will be able to walk from A to C, ignoring B. The specific route from A to C does not have to be taught. However, Lockman et al. (1981) and Reiser et al. (1980) find the more experience one has with travelling without sight the more accurate the response to spatial-layout tasks.

Wagner et al. (1996) explored the connection between stepping motions and spatial judgments. Using a treadmill, they varied the rate at which a step changed the observer's spatial location. Subjects swiftly adopted the new coordination. The effect was perceptual, not a conscious correction, because there was an aftereffect once the normal coordination was restored.

Morrongiello et al. (1995) videorecorded blind and blindfolded-sighted children undertaking the Landau ABCD four-locations task. They coded the paths taken, accuracy of initial turns, closest positions and final positions relative to the target locations. They also devised a composite score to assess the efficiency of the path taken. The mean age of the blind children was about 7 years, with a range from 4 years 5 months to 9 years two months. The children were all congenitally totally blind (that is, none had ever had sensitivity to light). The blind children performed like the sighted children on all the measures except accuracy of the final position, at which they were slightly worse.

The children were also asked to draw some visible or tactile maps, e.g. showing the route from B to D. The proportion of sighted children who drew correct maps of their routes was about 20% for visible maps or tactile maps at age 4–5. At age 6–7, the proportions were still about 20% for visible maps, but had risen to 33% for tactile maps! At age 8–9, the proportions were 50% for visible maps and 58% for tactile maps. The majority of the children received the same score for both maps. Evidently, the map-making ability is modest

in preschoolers, grows slowly, and tactile-map making is at least the equal of visible-map making. The tasks tap just one ability, in the sighted at least, it seems likely.

Morrongiello et al. note that "examining the nature of spatial representation is a challenging task because of ambiguity in the link between representations and behaviour" (p. 228). This was one reason their study used three tasks. On their easiest task – walking between the ABCD destinations – only a few of their youngest subjects accurately reproduced distance and angle information when pursuing novel routes. No three-year-old available to the investigators could be persuaded to undertake the task. In contrast, the actual routes on which the subjects were trained, and reversals of the routes, were executed summarily.

6. Measures of spatial ability

Were the youngest children discussed in Morrongiello et al. (1995) ever reluctant to run novel routes for fear of novel obstacles? Could they have pointed in the right direction (from B to D)? Standing at B could they have told whether a sounding brass or a tinkling cymbal was located at D or C or A? Some response measures are more revealing of basic spatial representations than others (Millar, 1985, 1994).

Haber, Haber, Penningroth, Novak and Radgowski (1993) tested body postures, including the use of limbs, fingers, noses or attached sticks as pointers. Which best indicate the directions of sound sources? The subjects were twenty blind adults. The sources occupied a semicircle from the extreme left, through straight ahead to the extreme right. The body parts to be pointed at the target included the index finger of an outstretched arm, the observer's nose and the chest, to which a pointer was affixed at right angles. The observers also tried to point hand-held rods at the target. All these measures were superior to methods that used external pointers on their own bases, like rotating a dial. The least accurate methods involved drawing or offering a verbal description using clockface labels such as noon for extreme left, 3pm for straight ahead and 6pm for extreme right. Generally, the body part or hand-held rod methods were less variable as well as more accurate.

Subjects who travelled less in everyday life were particularly poor at the more difficult tasks and those with high variance such as the clock-face or drawing tasks. On the other tasks, the groups performed alike. Travel skills and experience may affect performance on relatively indirect measures of space

perception, and have little bearing on basic body orientation to the local environment, it seems (Millar, 1985).

7. Triangular routes and convergence

Worchel (1950) argued blind people guided along a right-angled triangle route from origin A to the right angle at B and then to a terminus C often cannot then walk back from C to A along the hypoteneuse. This extreme claim is surely false (Klatzky et al., 1990; Millar, 1994, 1997, 2000). Errors will be made, but the basic principle that the triangle exists in a two dimensional space, with directions and spatial extents, is understood by most blind people intuitively, provided they have no loss other than sight (Kennedy and Campbell, 1985). That is, the blind person knows that extents subtend smaller and smaller angles at our vantage point as they recede: Directions to the ends of the extent converge.

The principle of convergence applies in both the horizontal plane and the vertical plane. We can point to the bottom and top of nearby and distant trees or to the gaps between vertical columns that are near and far. Both entail convergence. If we point upwards to a bird flying away from directly above our head we will find the direction changes swiftly at first and then more slowly. Likewise, if we point to a mouse running away from between our feet we find the directions change swiftly at first and then slowly. Generally, blind people understand this (Kennedy, 1993). If our left arm is pointing up to the bird in the sky and our right points down to the mouse on the ground, they start to converge. They converge more and more slowly as the imagined distances of the bird and mouse increase. Both arms stop at the horizontal. When they stop they are pointing at the horizon.

The principle of convergence applies to all dimensions of space. It applies to small scales – the tabletop or manipulative space – and to larger scales such as the domestic or room-sized space and the ambulatory space of say a few hours walk (Millar, 1994, 2000).

The space to which convergence applies consists of directions (angles) and distances from a vantage point. Do we confuse these two? Klatzky (1999) measured angle and distance errors in touch, finding they were often minor and usually unrelated.

Klatzky (1999) looked for the origins of systematic errors made when blindfolded subjects attempt to walk two legs of a triangle and then to indicate where the origin is from the final destination. She asked whether errors are introduced when subjects attempt to imagine their walk and final destina-

tion has been displaced by a rotation about the terminus, or by displacement to one side. She found more errors for distances than directions (angles). Interestingly, she suggests some errors are due to subjects emphasing body-centred coordinates: information about space is referred to the observer's vantage point, and any errors arise from misestimating the body's location and where it is facing (Philbeck et al., 2001). Other errors, she argues, come from use of objects or landmarks as the primary basis for spatial understanding: object-centred coordinates. She contends body-centred errors are more evident before subjects entertain imagined rotations (yaw) or displacements. But object-centered errors are more common after imagined rotations. These somewhat different effects may help distinguish percepts during actual changes from beliefs after some imagined shifts.

Despite the presence of some errors, the subjects tested by Haber et al., and by Klatzky, performed quite consistently and often accurately in spatial tasks, whether they were in the target location, or imagining locations, directions or displacements. In this vein, Kappers and Koenderink (1999) found errors in tactile spatial judgments were not correlated with distance (forward and backward directions), though judgments made using right and left directions were prone to systematic errors – often major ones! When subjects were asked to set a test bar to our left parallel to a reference bar on our right, they often made large errors (such as 40 degrees from parallel). One can demonstrate this effect easily. With one's eyes closed, reach out with the right arm to place a pencil on your far right, say on your desktop. Then reach out to place another pencil to the far left, say with the left arm. Make the two pencils parallel. Then open your eyes. The pencils will not look at all parallel. (Perhaps we used two tactual vantage points, such as the left and right shoulders, one for each pencil.) However, if one pencil is just in front of us, pointing away, and the other is further away, we can align them with little error. Kappers and Koenderink (1999) conclude this systematic source of frequent errors in left–right matters reveals haptic space is not fully Euclidean. Why we are more accurate in distance than when dealing with left and right remains unclear, but it is surely familiar to most of us, blind or sighted, that left and right get mixed up in many ways. A series of investigations from the Koenderink and Kappers group maps out the systematic reliable errors in very convincing fashion. Tactually, the left–right continuum presents dramatic challenges unknown to distance. As a result, comparisons of distances straight-ahead and distances left–right are full of error (Cabe et al., in prep.). Heller and Joyner (1993) find an inverted-T shape gives us the impression the left–right crossbar equals the stem receding in distance when it is 30% larger, for many subjects. The threshold for length differences is likely

similar in both directions (about 1 in 15), and if so this inverted-T illusion is to do with judgments influenced by patterns. Perceptual factors such as foreshortening may explain such effects with visual Ts, and, extraordinarily, it may be some related principles work in touch, as we have noted. Indeed, Millar and Al-Attar (2000) argue some of the inverted-T tactile-illusion effects are due to spatial reference, as subjects try relating the parts of the pattern to landmarks and body coordinates much as they would if they were looking at the pattern.

8. Pictures and the field of directions from a vantage point

When we use a picture, the very medium of picturing has distinctive implications about orientations (Pierantoni, 1986). We can look at a picture pinned to a wall, and take it to show a person in profile standing upright. If we take the picture off the wall and lay it on our desk it will be horizontal. Does this make the man appear to be lying down? Well, no. We take the picture to be a medium whose vertical or horizontal orientation is not relevant to the orientation of the profile (Kennedy, 1993). The profile remains that of a person standing erect.

However consider the picture lying on the table. The profile can be turned so that its nose points toward the observer, or away from the observer. Then blind and sighted subjects can be asked when the profile seems to be facing down to the ground and when it faces up to the sky. Like others I have tested, LT, a totally blind man, whose blindness had an early onset due to retinitis pigmentosa, reported when the nose (in a horizontal picture, made of raised lines) was pointing towards him the profile seemed to be facing the ground. When the nose was pointing away from him, the profile was facing up to the sky.

The profile demonstration suggests people use a field of directions around a vantage point centred on their heads to interpret tactile pictures. What is higher in the field of directions is taken as representing objects that are higher in the vertical plane in the world. As another example of this use of a field of directions, consider the text on this page. Notice that the text can be read while resting on the table, vertical as if fixed to a wall, or held overhead as though fixed to a ceiling. Sometimes the text letters have their tops farther from the observer than their bottoms, as is the case when they are on the table. Sometimes the tops of the letters are closer to the observer than their bottoms, as is the case when they are on the ceiling. But in both cases the tops of the letters are higher in the field of directions than the bottoms. And in both cases the letters appear upright (Mirabella and Kennedy, 1999).

If someone draws a U on our hand as it lies palm-up on a table in front of us, and we have our eyes closed, we can read it as a U. If we turn our forearm to bring the hand in front of our tummy, palm up, thumb pointing away from us, still resting on the table, the same shape on our skin will usually be read as a C. This suggests the vantage point at our head controls the apparent shape and identity of the form traced on our skin. What is higher in the field of directions from that vantage point is the top of the letter.

Many investigators have used "cutaneous perception" tasks in which a letter is drawn on the skin, with a blunt stylus, on sites scattered around the observer's body. Subjects seem to entertain a variety of vantage points in three dimensions. Natsoulas (1966) drew b, d, p and q on the subject's forehead. Subjects generally used one of two vantage points, the results suggested. One had an internal location. The subject behaved as if looking from a position within their head. The second had an external location, like a "disembodied eye" (Concoran, 1977) in a nearby space. The subject behaved as if looking from the experimenter's position standing in front of the subject (having imagined moving forward, then facing back). Often subjects could readily change from one apparent vantage point to another nearby (but not always, for inversions are difficult to entertain). Similar flexibility of vantage points in assessing forms drawn on the skin is evident in studies on blind subjects (Shimojo, Sasaki, Parsons and Torii, 1989). Further, the confusions subjects report are between p and q, or b and d. Subjects maintain the vertical orientation of forms on the forehead. Inversion is very rare.

The studies on profiles and letter forms suggest what is high in the field of directions around a vantage point is the top of the object, whether the form is on a table, a wall, a palm or a forehead. But they also suggest vantage points that are disembodied can move forward horizontally fairly readily. It is also relatively easy to imagine being elevated above an array of objects, with "a bird's eye view", as tactile maps often require us to do. But rotation of a vantage point with its field of directions from erect to tilted or inverted (a roll, as opposed to yaw or pitch) is not easily entertained by the observer. Because it changes directions from a vantage point, rotation of tactile displays in the plane by 180 degrees makes them hard to recognize (Kennedy and Bai, 1999). Similarly rotation of visual maps on our lap in the car often confuses navigators about left and right.

9. Arcs and elevators

One kind of rotation moves the object in a vertical arc around the vantage point (pitch), from a table surface to the ceiling. Objects with conventional fronts such as raised letters and pictures can move in an arc like this and remain upright, apparently facing us and easily legible. Their orientation is invariant across this arc. Their orientation is always taken as facing the vantage point, and their top is the upper part in our field of directions. Orientation and direction are related concepts, by definition. A tactile vantage point is precisely a location from which the orientation of the object with respect to the six degrees of vantage-point change can be established.

Some objects maintain their orientation in an up-down or elevator transformation but not an arc. Cups would spill their contents if moved in an arc, but elevated vertically from a desktop to a shelf they keep their usefulness (that is, their "affordances", Gibson, 1979). They are directed upwards, much as is an elevator. The elevator transformation is often independent of any single vantage point. But the arc has a unique vantage point as its origin. The elevator transformation, however, can take an object past the level of our vantage point. The cup varies in its accessability, for it can be too low or too high for our reach, from a given vantage point. Also, when we imagine a bird's eye view on a room we have often raised our vantage point as if on an elevator, while maintaining what is to our front and back, left and right, and likely this is straightforward for many blind and sighted observers. (A birds's eye view may be what Haber et al.'s observers undertook when asked to report distances in one room while sitting in another room. If the blind and sighted observers inadvertently combined an awareness of the room's true proportions with an impression of the size of a relatively small map showing the whole room from above, that could explain the diminution in size Haber et al. found.) If we combine elevator and sideways movements we would reveal tops and sides of blocks simultaneously. Combinations have more implications than one shift, and are surely harder to deal with intuitively. When we just move left or right (slide), or to the front or back (to-and-fro) we maintain what is higher or lower than us. These motions preserve direction – what is straight ahead on the horizon – tactually and visually. Again, these motions of just one factor defining the vantage point in a plane are familiar to the blind and the sighted, surely.

The elevator transformation does not invert an object. But a raise of our own vantage point helps reveal the tops of solid objects (and lowering ourselves reveals the bottoms). The arc transformation does not invert a tactile picture when it moves from a table to overhead. But if the display passes overhead and

starts downwards again (behind us, for example) it inverts while following the arc. Both inverted solid objects and pictures likely are relatively hard to identify in touch whether we roll or the object inverts. A u-shape becomes an n-shape. Model heads and cookie cutters that are inverted are often hard to identify in touch, my informal class demonstrations find.

In sum, the apparent orientation of an object, or pictured object, at a tactile vantage point is often dependent on a field of directions from that point. The vantage point may be disembodied to some extent, and in a variety of locations in the three dimensional space around the observer, with the locus moved forward or back, displaced to one side or elevated. As Klatzky pointed out, it can rotate in the plane to some extent, remaining upright, and still be quite usable. Invariant upright orientations of targets facilitate tactile perception of form, it is likely. An extended arc or roll around a vantage point eventually impairs recognition severely. Left–right slide, elevator motion and yaw, moving around an object, have some modest effects, especially on percepts related to judgments of parallels, it may be. Change of distance to-and-fro may have relatively little effect on recognition. Combinations of several of the six degrees of freedom of directions likely are hard to follow.

10. Borders, media and foreground in vision and touch

A disembodied vantage point with directions to a few objects can be envisaged relatively freely. It can be where we intend to shift, before we actually go there. But much of our tactile exploration aims to use richer or fuller environments, with real edges of actual surfaces (and the continuous textures between the edges) being examined to determine where we are in relation to objects. Similarly much of vision involves scanning borders of various kinds to get to know the vista around us and our place in it.

How do vision and touch use surfaces, textures and borders, and the media of perception, to define where we are? Rubin (1915) described a kind of foreground and background perceived at a contour or line as figure and ground. We can add that our vantage point is always indicated by what is foreground and background.

A line or contour can be defined by colour or luminance borders in vision. What operates in a similar vein in touch? Touch reveals borders of surfaces as changes in resistance, notably, and thermal and wetness or friction properties secondarily. We can certainly feel a foreground surface overlapping a background surface. One example is we can feel that a sheet of newspaper is lying

on a rubber mat such as a mouse pad. Further, we can feel one section of our newspaper is lying on and partially covering another, and that on another, and that on yet another etc. We feel a set of foregrounds and backgrounds. They specify that our vantage point is in front of the most foreground sheet.

A flat surface offers resistance, ending at a border, giving way to another kind of resistance. We can also feel two similar surfaces meeting at a corner, with change in slant (where the top of our desk meets a wall, say). The corner encloses our vantage point, if the corner is concave. We are outside the corner, we feel, if it is convex, like the corner where the top of our desk meets its side. A roofline of a model house is a tangible border (Heller et al., 1995; Heller et al., 1996). A rounded object seems to offer a definite border between front and back to vision, and it also offers a border to touch if we take it to be in front of a particular vantage point, say one from which we are reaching. To that vantage point, the object presents a front, a back and a clear division between the two: an occluding boundary of a rounded surface.

Raised line drawings of objects showing corners and boundaries of rounded surfaces by lines are recognized in remarkably similar fashion by blind and blindfolded sighted 8–13 year olds (D'Angiulli et al., 1998; D'Angiulli and Kennedy, 2000). The blind children were congenitally totally blind. The performances of the sighted and the blind children were highly related, indeed the scores of the blind and sighted children exploring the displays actively, with no external guidance, were correlated .81.

Perhaps some aspects of textures operate similarly in vision and touch. A sheet of paper and a rubber mouse pad have tangible textures, just as they have visual textures. Variation in tactile texture is readily used as an indicator of the slopes of surfaces, though it may be more immediately understandable in vision (Holmes et al., 1998). Holmes et al. presented blindfolded subjects with texture patterns with distinct gradients, say dense at the top and gradually expanding to sparse at the bottom. In the series of patterns, the rate at which the texture expanded was varied. Subjects attempted to match the texture patterns to panels that sloped from vertical to nearly horizontal. Subjects scaled the magnitudes of the physical slants of the panels to suitable texture gradients, provided the extremes of both were evident and some opportunities for learning were offered. Early blind subjects performed like sighted subjects.

Vision also uses changes in the visibility of textures to indicate what is foreground and background. Is there an equivalent at a tactile vantage point? Consider the possible cases. "Accretion" of texture is texture becoming evident in the optic array at our vantage point. "Deletion" is the reverse. Gibson (1979) described a surface being pulled out from under a cover, such as a newspaper,

as specified by its texture visibly accreting at its common border with the paper. If the motion is reversed, and it is progressively covered by the foreground newspaper being pushed on top of it, the surface's texture is optically deleted.

Is there a tactile equivalent for Gibson's case? Certainly we can feel a mousepad's texture moving out from under a cover sheet, accreting in touch, indicating it was behind the cover and is now being exposed. And we also can feel a cover sheet being pulled over the pad and concealing its texture.

Besides Gibson's case, vision also involves texture accretion and deletion occurring because of illumination, and a rather different kind that occurs when the medium for light transmission has elements swirling in it. A searchlight playing over a prison wall in a 1930's black-and-white movie often reveals the wall's texture of bricks accreting at the leading edge of the pool of light. The texture at the trailing edge is deleted, falling into invisibility. The accretion and deletion specify a single surface, the wall as foreground, with no other surface as background. Shadows racing over the wall have similar effects (Kennedy, 2001).

A searchlight beam passing through empty air is invisible till it hits a reflector (the wall, in this prison movie). To add to our little drama, consider the night air is full of twirling snowflakes, gently falling. The snow may be invisible till it enters the searchlight beam (optically accretes). It passes into invisibility again when it falls through (deletes). The accretion specifies the texture elements are in the foreground. So too does the deletion. The elements in turn specify a volume of space, which we often informally call the searchlight beam.

Snow in daylight can provide another case of accretion and deletion. If our vantage point is in front of a dark surface, such as a dark pinetree-covered hill (one at the far end of a snow-covered field with its topmost trees silhouetted against a white sky) falling snow may only be visible when it has the hill as background. That is, the snow can be invisible against the sky. It only comes into view when it is in front of the hill from our vantage point. It is invisible again when it is against the snow-covered field. From our vantage point, the accretion of snow at the brow of the hill specifies a volume of elements in front of the dark border, and the deletion at the border at the base of the hill does the same.

Touch is hardly as richly endowed as vision with cases of accretion and deletion. Touch generally operates more like an eye scanning over elements on a fixed surface. We often look at an element, allow it to fall into our periphery, and then gaze away so the element is too far to the side to be seen. Similarly, when touch runs a hand over a surface, texture elements come onto our skin, pass across the skin, and then fall too far behind to be in contact. However, we are not totally without some tactile media. In addition to direct contact, touch

can use a rod as an intervening medium to feel the roughness of a surface (Lederman, 1982). Textural roughness in the surface we are stroking causes vibrations to arise in the rod , and to vary as we pass over different surfaces. Further, touch can use covering material as a medium to palpate surfaces beyond the cover. The media through which we feel add their own roughnesses, vibrations and thermal properties we have to discount to detect the distal target. When we drive a car or ride a bike, the car or bike will tell us about the rough road we are careering over. They also add their own vibrations. That is, we often have to realize what arises because of media between our vantage point and the target. Touch isolates vibrations in a medley at our vantage point and discerns which are from the medium, which are from sources near to us and which are from afar.

In sum, like vision, touch offers accretion and deletion of texture from two surfaces in close proximity to each other. The event specifies foreground, background and our vantage point. Unlike vision, touch's use of media does not involve accretion and deletion due to a secondary source of energy, such as a searchlight, or texture in a medium accreting and deleting.

11. Coda

There are many ways in which vantage points arise in touch, in tactile tasks and in space perception served by touch, because touch deals with direction. Some show us limitations of the observer: Inversions and left–right comparisons are problematic. Likely large shifts of the vantage point, large shifts in directions, and combinations of many shifts of vantage points using several of the six degrees of freedom of a vantage point are also relatively hard to deal with. Some vantage points are disembodied, like intended locations, and some of these are easy to use. Some suggest practical ways of using pictures, using outlines for edges, and directions of elements in the picture to stand for directions of referents. Some are especially easy to use because they involve invariants in the real or represented orientations of moving objects. Some allow perspective to be present and active in touch. The parallels with vision are extensive, as consideration of direction shows, but not complete, as consideration of accretion and deletion of snow in a spotlight reveals.

I may have left the impression that vision's vantage point is plain at all times. This was handy to introduce my topic. But I should not let it go at that. Our visual impression that we have a single vantage point optically is deceptive. We look with two eyes, not one. But objects often seem to lie in one visual

direction. The laws of visual direction, and the conditions under which we will seem to have one visual vantage point, are now a subject for animated debate (Ono and Mapp, 1995). It seems fitting that we should realize we could try to discover the laws of vantage points in touch just as fresh views of visual vantage points are being explored.

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CHAPTER 8

'Berkeley's touch'

Is only one sensory modality the basis of the perception of reality?

Alf C. Zimmer

> ... I believe whoever will look narrowly into his own Thoughts, and examin what he means by saying, he sees this, or that thing at a Distance, will agree with me that, what he sees only suggests to his Understanding, that after having passed a certain Distance, to be measur'd by the Motion of his Body, which is perceivable by Touch, he shall come to perceive such, and such Tangible Ideas which have been usually connected with such and such Visible *Ideas*.
>
> (George Berkeley, *An Essay towards a New Theory of Vision*, Dublin, 1709), Zitat XLV.

In this quote George Berkeley proposes the dogma,[1] that space is perceived by touch and that only secondarily by associating tactual with visual perceptions the perceiver grows accustomed to the notion of visual perception of space. This claim that touch is the primary sense organ for perceiving reality has determined much of the discussion about perception in the age of Enlightenment and still influences popular theories of perceptual development (see Jean Piaget, 1969).

The very core of this argument is captured in Dr. William Molyneux's question as quoted by John Locke (1694): "I agree with this thinking Gent ... and am of opinion, that the Blind Man, at first sight, would not be able with certainty to say, which was the Globe, which the Cube, whilst he only saw them: though he could unerringly name them by his touch, and certainly distinguish them by the difference of the Figures felt" (pp. 67–68). In John Locke's theoretical framework, the complex idea of space relies on tactual sensations leading to the ideas of objects. Despite his objections against Locke's empiricism, George Berkeley answers Molyneux's question in the negative: "... a Man born Blind and made to See, wou'd, at first opening of his Eyes, make a very different

Judgment of the Magnitude of Objects intromitted by them, from what others do. He wou'd not consider the Ideas of Sight with reference to, or as having Connexion with, the *Ideas* of Touch." (p. 93)

The question if someone born blind will be able to identify known objects by looking at them after he has been operated has later motivated Etienne Abbé de Condillac (1754) to develop an empiristic theory of perception based upon touch as the primary sense organ. "It is true that we do not notice the judgments we make in order to grasp the whole of a circle or square ..." (Also see Denis Diderot (1749): "It follows ... that we owe to experience the notion of permanent objects; that by touch we acquire that of their distance; that perhaps the eye must learn to see as the tongue to speak").

Upon this theoretical background one has to regard the development of psychophysics in beginning of the 19th century starting with Ernst H. Weber's investigations "de tactu" of 1834 and "Der Tastsinn und das Gemeingefühl" of 1846. In a similar fashion the development of empiristic theories of space perception by Rudolph Lotze (1852), Hermann Helmholtz (1866), and Wilhelm Wundt (1896) have been influenced by George Berkeley's dogma of the primacy of touch. The quintessence of these theories starts from the notion that only by touching objects or being touched by them, by moving objects or moving our bodies and limbs towards them we experience reality directly. Associating these direct experiences with the sensory data given by the eye, spatial vision becomes possible; insofar visual perception can be regarded as a indirect – and therefore symbolic representations of the touchable reality, for this reason these perceptual modalities can be regarded as analogous to language.[2]

The primacy of touch as understood by Ernst Weber had direct consequences for his experimental methods and their generalization to other sensory channels: "My results on the perception of weights by the tactual sense are therefore valid for the visual perception of length, too." Especially Jean Piaget's "The mechanism of perception" (1969) has popularized George Berkeley's dogma with direct consequences for the education of young children; according to his claims e.g. young children born blind should not be able to make short-cuts in their explorations of space because making short-cuts without visual information depends on the formal operation of computing the cosine. Contrary to this claim, these children are able to make short cuts: a result which either contradicts Jean Piaget's stage theory of cognitive development or implies that tactual space perception cannot be the basis of geometric space.

George Berkeley's argument concerning the epistemological primacy of touch radicalizes the Stoic point of view on the criteria of reality (Sextus Empiricus, Pyrrhonic scepsis I, 228); according to which "real knowledge" relies

on touching and manipulating objects. In many Indo-European languages this epistemological point of view is implicit: see for instance the English words 'concept' or 'percept' which both derive from the latin 'capere', it is even more obvious in Germanic languages e.g. in German *Begriff* (concept) from *Greifen* (grasp or catch) und *Wahrnehmen* (perceive) from *wahr* (true) und *nehmen* (take): Taking as true or 'grasping reality' this corresponds well to the fact that real size can only be perceived by touching; the seen size in contrast depends on the distance between the perceiver and the object; especially the Ponzo illusion shows how variable the vision impression of size is. However, the phenomenon of visual dominance as shown in the Ames room reveals that in the case of discrepancies between haptics and visus the visual perception prevails over the (correct) haptic perception.

Aristotle vindicated visual perception as a medium for grasping reality by claiming that not isolated sensations but the invariance of the relative motions of objects and perceivers constitute the veridicality of visual perception, a point of view which became focal in James Gibson's ecological perception (1979). Aristoteles attacked the Stoic reliance on touch even directly by reporting a stunning illusion of touch: If one crosses the index and the middle finger and touches **one** object, **two** objects are perceived. This indicates that tactile perception relies on top-down processes too, insofar as the act of perceiving relies on representations of the world in the mind of the perceiver.

Aristoteles' observation constitutes an argument against classifying touching as a "lower" sense modality in comparison to seeing or hearing because this classification of senses divides them according to be criterion of complexity: "lower" sense modalities are directly and entirely tuned to changes in a single physical dimension, in contrast "higher" sense modalities allow the identification of objects (in vision: forms and symbols, and in audition: melodies and phonemes which a turn stand for symbols). If the Aristotelian illusion indicates that tactual experiences rely on internal representation as much as hearing or seeing, touch has to be classified as an object-oriented sense modality, however, in this case touch lacks the immediacy of perception which John Locke and George Berkeley presuppose when postulating the primacy of touch. Furthermore the apparent "wisdom of language" and even self observations relying on verbal reports have to be regarded with caution, as a remark by David Katz (1925) shows, namely that the strong parallelism between perceiving and acting might go back to one feature of Indo-European languages where perceptions "rule the accusative" as actions do; in contrast the Khartvelian languages (e.g. Georgian); they differ just in this feature from Indo-European languages but in most other syntactic constructions are comparable.

Since the times of William Molineux a couple of cases have been documented where congenitally blind have gained vision; all these cases indicate that these people are able to visually identify objects which up to then they have only experienced tactually (see Richard L. Gregory, 1970; Michael J. Morgan, 1977). The limits of the intersensory coordination become apparent in the drawings of this people which show that – at least in the beginning – these people are only able to depict those parts of object which are accessible by touch (see Figure 1); for instance, they cannot 'comprehend' shadows.

A further neuropsychological argument for the coordination of vision and touch constitute the results of the research group of Paul Bach y Rita (1972): they show that congenitally blind people are able to identify objects the picture of which has been transformed into a vibration pattern on their back (see Figure 2).

On this principle rely assistive instruments for blind people as e.g. the Optacon (Paul Bach-y-Rita et al., 1969).

This example of the coordination of different sense modalities support the Gestaltist postulate of perception as an objects-directed process. Michael S.A. Graziano & Charles G. Gross (1995) found bi-modal cells in the parietal lobe of monkeys that respond both to the tactile and corresponding visual stimulations. Most important is that in contrast to the standard Hubel & Wiesel-type of receptive fields the visual response of these neurons is not related to the position of the retina but to the position the body of the perceiving animal.[3]

Well before these neuropsychological and neuroanatomical results in favor of perception as the result of intersensory cooperation and not of a hierarchical order, functional analyses and comparisons of the tactual and visual sense modalities have been undertaken. The epistemological motivation behind these analyses has been on the one hand the refutation of George Berkeley's dogma and on the other hand the notion of perception as an aggregation of sense data. Using a similar chain of argumentation as Aristotle in his critique of the stoic position, by showing the parallelism of vision and touch in regard to perceptual illusion, Berkeley's dogma of the priority of touch was put into question.

Starting with A.W. Volkmann (1858) and – probably not – ending with V.H. Franz, Karl Gegenfurtner, Heinrich H. Bülthoff, and Manfred Fahle (2000) the following classes of illusions have been analyzed for the parallelism between vision and touch:

(a)

(b)

(c)

Figure 1. Drawings of congenitally blind people after an operation giving them vision.

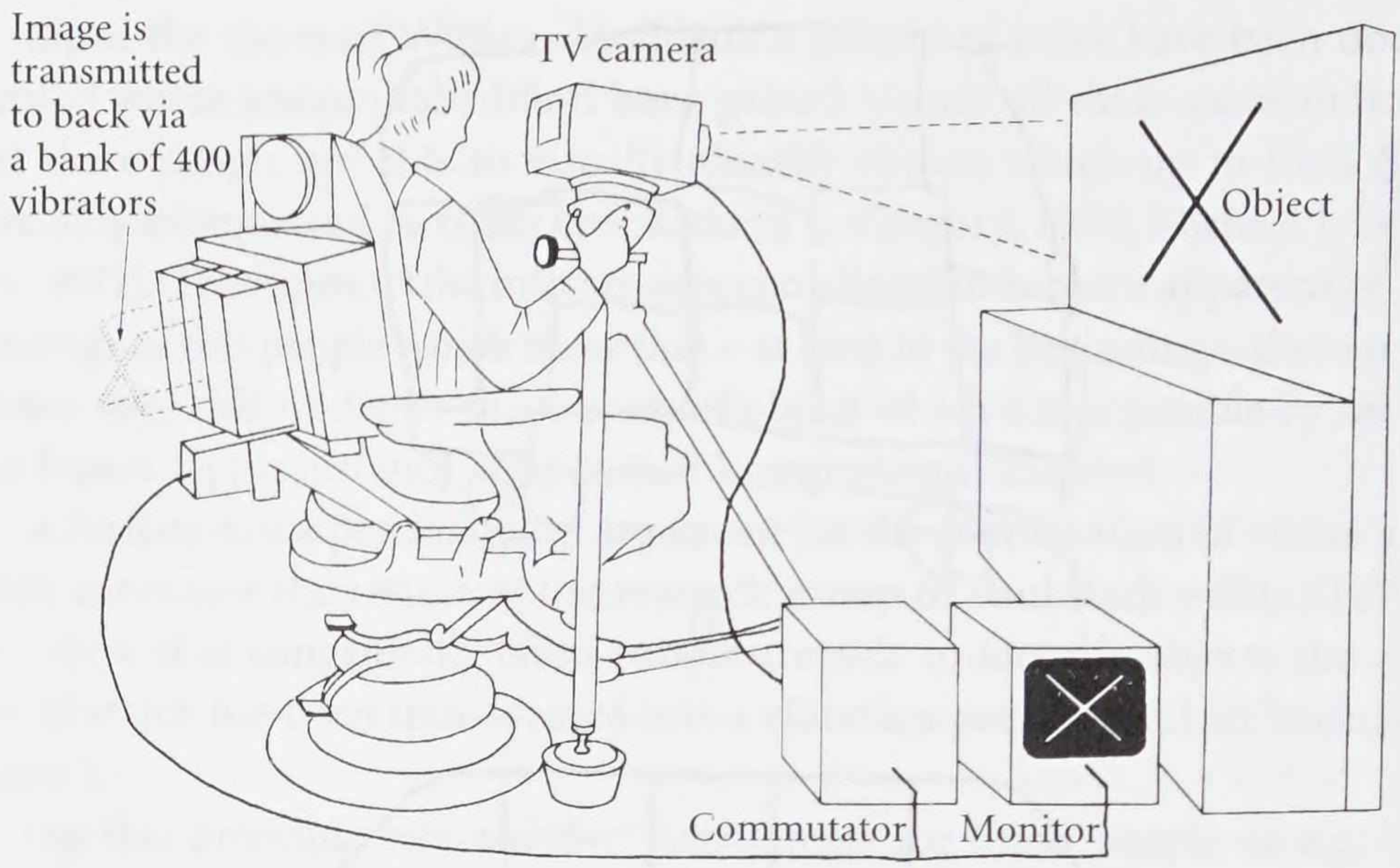
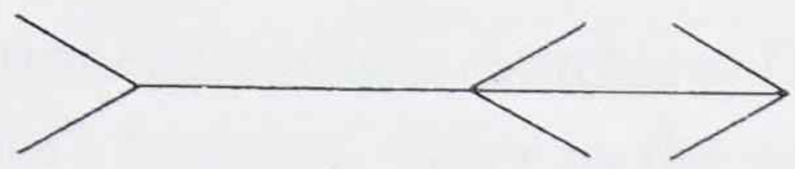


Figure 2. The apparatus used by the research group of Bach y Rita.

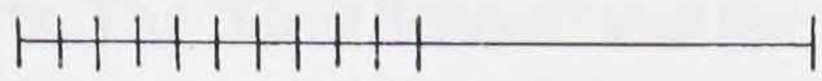
1. The Oppel-Kundt-Illusion: Parrish (1895), Robertson (1902), Volkmann (1858);
2. The Müller-Lyer-Illusion: Over (1968), Patterson & Deffenbacher (1972), Rudel & Teuber (1963), Tsai (1967), Wong (1975a);
3. The vertical-horizontal-illusion: Frey & Craven (1972), Künnapas (1975), Reid (1954), Tedford & Tudor (1969), Wong (1975b), Wong (1977);
4. The Poggendorf-Illusion: Fisher (1966), Pasnak & Ahr (1970);
5. The Ponzo-Illusion: Leibowitz & Pick (1972);
6. Illusory motion: Benussi (1916);
7. The Bourdon-Illusion: Day (1990);
8. The Ebbinghaus (Titchener) illusion: Franz, Gegenfurtner, Bülthoff, Fahle (2000).

Overviews and epistemological interpretations of these experiments can be found in: Fechner (1860), Sobeski (1903), Rieber (1903), Jaensch (1906), Révész (1934), Hippius (1937), Révész (1938), Révész (1953), Scholtz (1957/58), Hatwell (1960), Over (1966), Katz (1969), Huntley & Yarus (1973), Frey (1975).

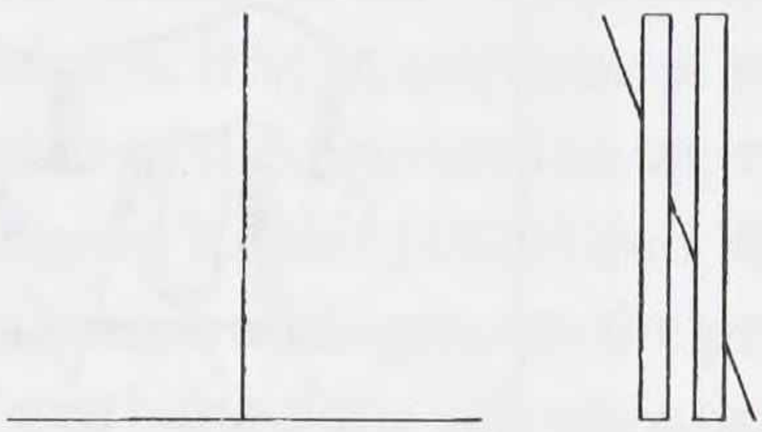
Richard Gregory's argument (1970) that all geometric optical illusions are due to the experiences of the spatial environment and their representation in pictures and that the effect of illusion-inducing patterns should vanish if these experiences are lacking, have been refuted by the experimental results of Herschel W. Leibowitz and Herbert A. Pick (1972) showing that the Ponzo-illusion



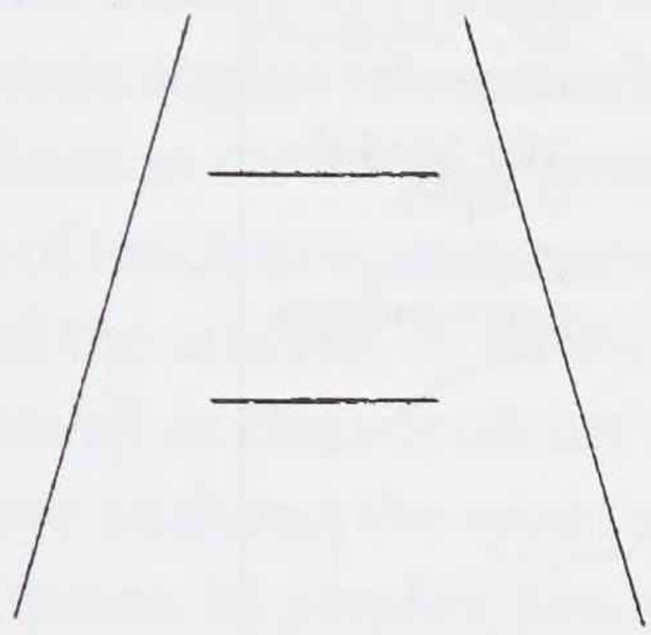
Müller-lyer



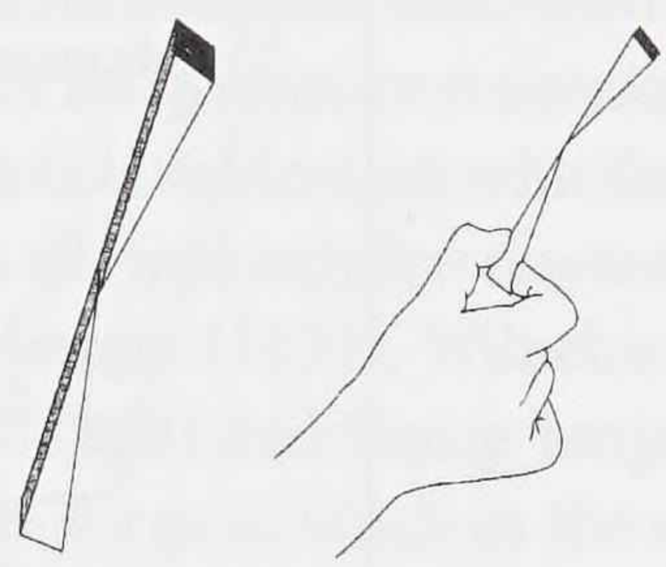
Oppel-Kundt



Vertikal-horizontal Poggendorf



Ponzo



(a) (b)

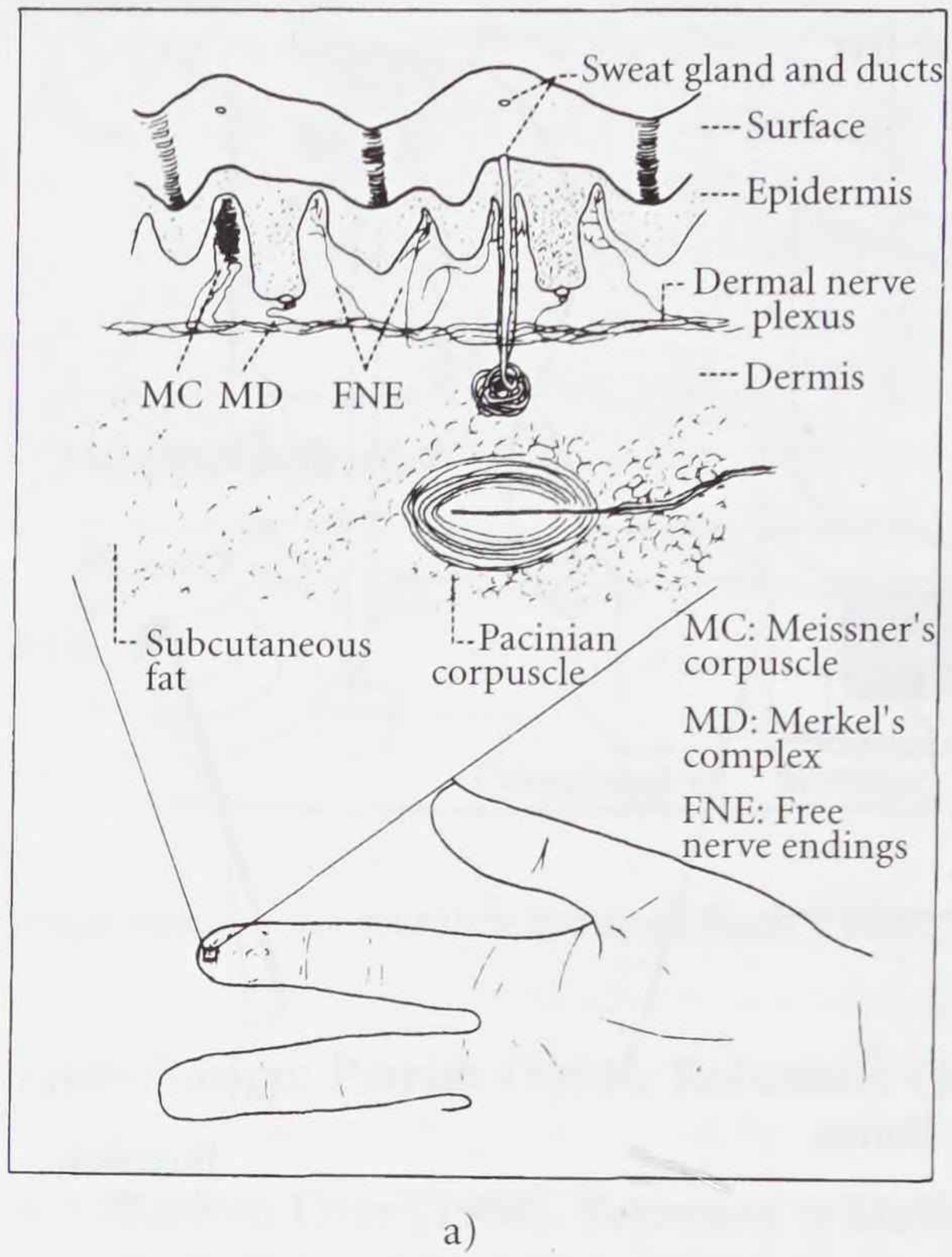
Bourdon

Figure 3. Geometric-optical illusions having an analogous effect on touch.

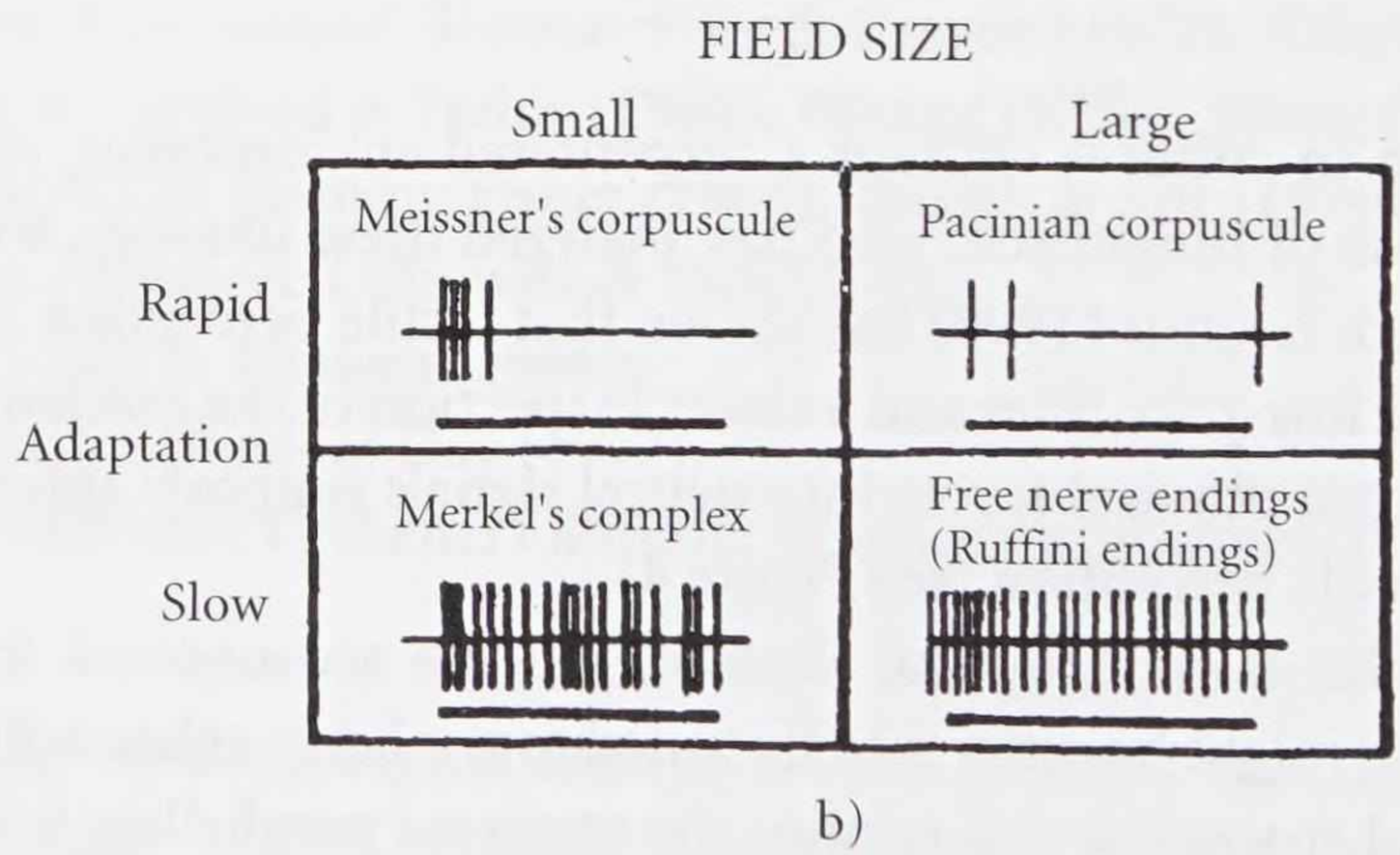
can be shown in cultures without a carpentered environment, and other results, e.g. those of Jungnitsch, who has analyzed these illusions with congenitally blind. Jack Loomis (1990) has shown that tactile perception has the characteristics of a low-pass-filter and a closer inspection of the mechano-receptors which transform physical forces into neural signals supports this view at least for passive tactile perception (see Figure 4).

In a similar fashion optical illusions can be accountered for low-pass-filtering which might be differentially tuned to the body-related dimensions of the perceptual space. For this reasons the apparent parallelism between visual perception and passive tactile perception can be caused by the same physiological process of low-pass-filtering and therefore the analyses of tactual illusions are irrelevant for the critical appraisal of George Berkeley's dogma or at least not conclusive.

Gestalt Theory, starting with Christian v. Ehrenfels (1890)[4] referring to Ernst Mach's phenomenon of the perceptual identity of melodies under transpositions regarded perception in general as object-oriented despite the above



a)



b)

Figure 4. The anatomical and functional features underlying haptic perception. a) The structure of glabrous skin, as illustrated by a section through the finger pad (adapted from Vallbo & Johansson, 1978); b) The neuronal responses to an indentation (⌉⌊⌈) in the four haptic receptors which can be classified according to fieldsize and speed of adaptation.

mentioned linguistic cautelae of David Katz. The "Graz School" and the "Berlin School", however, differ in the postulated processes for bridging the gap between perceived objects and sense data. According to the "Graz School" and especially for Vittorio Benussi (1916) invariants, that is, relations of relations, constitute the perceptual objects, this reminds of the Aristotelian approach. In contrast, the Berlin School (especially Wolfgang Köhler (1920) and Kurt Koffka, 1935) postulate processes of self-organization analogous to the properties of the electro-magnetic field; the driving force behind the self-organizing processes is the minimum principle which has motivated Frank Attneave (1981) to coin the expression "soap bubble psychology". Both Gestaltist accounts result in a positive answer to William Molineux's question and have motivated many Gestalt psychologists to experiment in the field of inter-sensory processes.

The fixation on the epistemological question in combination with the classification of touch as a passive sense modality has allowed only few researches to go beyond the analysis of illusions: Wolfgang Metzger (1954), Wilhelm Witte (1975) as well as their students Brigitte Färber (1980) and Georg Jungnitsch (1984) have analyzed the spontaneous and active form of touch in the exploration of forms. In parallel, James Gibson has demonstrated the veridicality of "Active Touch" (1962), an analysis influenced by David Katz (1924). These experimental results and especially James Gibson's approach of considering perception as a system tuned to object recognition is more important in shattering George Berkeley's dogma of the primacy of touch than the experimental results comparing visual and haptic effects of comparable illusion producing patterns.

If instead of passive tactile perception active touch is used for investigating three-dimensional objects and spatial arrangements, the comparison with the parallel visual processes makes the critique of George Berkeley's dogma even more conclusive. Wolfgang Metzger, Ortrud Vukovich-Voth and Ilse Koch (1970) have investigated the perception of the relative magnitude of parts of three-dimensional objects and have found consistent biasing effects. Georg Jungnitsch (1984) has shown how the "exploratory patterns" of congenitally blind and seeing subjects determine the amounts of illusion in a complex symmetric pattern. Congenitally blind and seeing subjects spontaneously use the following strategies of exploration (and even the relative proportion in both groups are similar): a) global touching, b) utilizing the finger width gliding with constant speed, and c) applying the bi-manual distance between fingers. Only the later strategy leads to differences between the two groups of subjects: congenitally blind use this strategy more often probably due to the fact that it is part of the training in rehabilitation centers for blind people. In general, Georg Jungnitsch (1984) shows that especially the contradictory results

regarding touch in the Oppel-Kundt-Illusion are the result of the different exploratory modes applied in the different experiments. For instance, the results of A.W. Volkmann (1858) rely on experiments allowing subjects to explore freely and to compare patterns in parallel, in contrast William James (1890) or Robertson (1902) obtained their contradicting results (favoring Berkeley's dogma) when requiring subjects to perceive passively.

The above mentioned low-pass-filtering characteristic of skin receptors can be partially overcome by active sequential exploration. Thus, only those comparisons of illusion in vision and touch bear on the question of George Berkeley's dogma which either are both active or both passive (the passive perception approach, however, generates further problems because it prevents subjects to apply the normal, that is, investigative perceptual processes). However, active exploration, that is, moving the hands in active touch or changing the point of view in seeing, reduces the effects of illusions, sometimes they even disappear. In both modalities not only object perception is possible but corresponds in such a way that cross-modal object recognition is possible as shown in the results reported by Richard Gregory (1970) and of the research group of Paul Bach y Rita. As early as in 1966 James Gibson has postulated that if perception is object-oriented then the senses interact in order to achieve this task by functioning as a unitary, albeit complex system. His postulate that perception is the result of a systemic interaction of senses makes the question of the priority of one sense modality a non-question.

William Molyneux's question as well as George Berkeley's dogma refer to the **origin** of experience. However, from a pragmatic point of view it might be even more interesting to investigate how the development of experience is shaped by modality-specific or modality-independent effects. Georg Jungnitsch (1984) was able to show that the more intense the experience of a subject with a specific pattern is and the more freely this subject is able to explore, the weaker the effects of tactual or visual illusions are. These results open the way for a more application oriented or pragmatic approach to George Berkeley's dogma.

Jack Loomis (1983) has investigated the performance data (precision of recognition) across both modalities with different symbol systems. Figure 5 shows six systems of haptic symbols corresponding in complexity.

Jack Loomis (1983) presented his subjects these different symbol systems either in haptic or in visual exploration conditions and tested them afterwards in the other sense modality. Figure 6 shows the relation between haptic (abscissa) and visual recognition performance (ordinate) for the different groups of symbols.

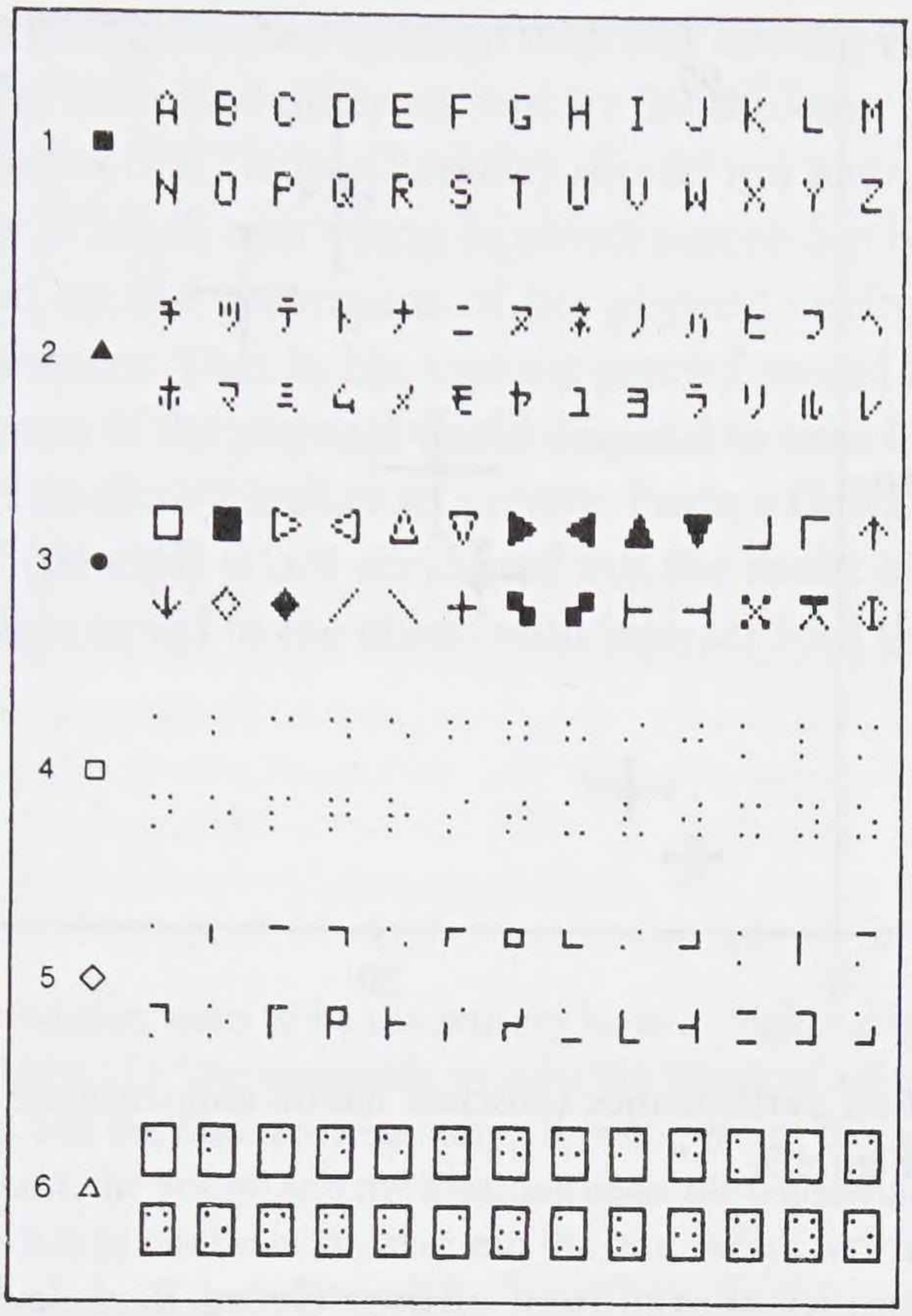


Figure 5. Patterns for tactile and visual form recognition (the symbols beside the numbers are used in the display of the data in Figure 6).

The data show the superiority of the Braille patterns (open square or open diamond) in comparison to other symbol systems (black circle, square, and triangle, open and black triangle). The difference between Latin (black squares) and Japanese (black triangle) letters is apparently due to the subjects' better knowledge of Latin letters. The extreme problems subjects had with the Braille symbols in frames shows that spatial masking reduces the recognition performance in both sense modalities equally. Despite the increasing variances of the data in the different sense modalities, the results in Figure 6 show a substantial parallelism between visual and haptic information processing. The tendency for slightly better visual recognition performance might stem from the effect that people with intact visus tend to use primarily visual symbol systems which makes them more easily learnable.

In conclusion: Experiments comparing haptic and visual performance have shown that not only perceptual illusions can be found in both sense modalities but that the effects in general are commensurable. This result is

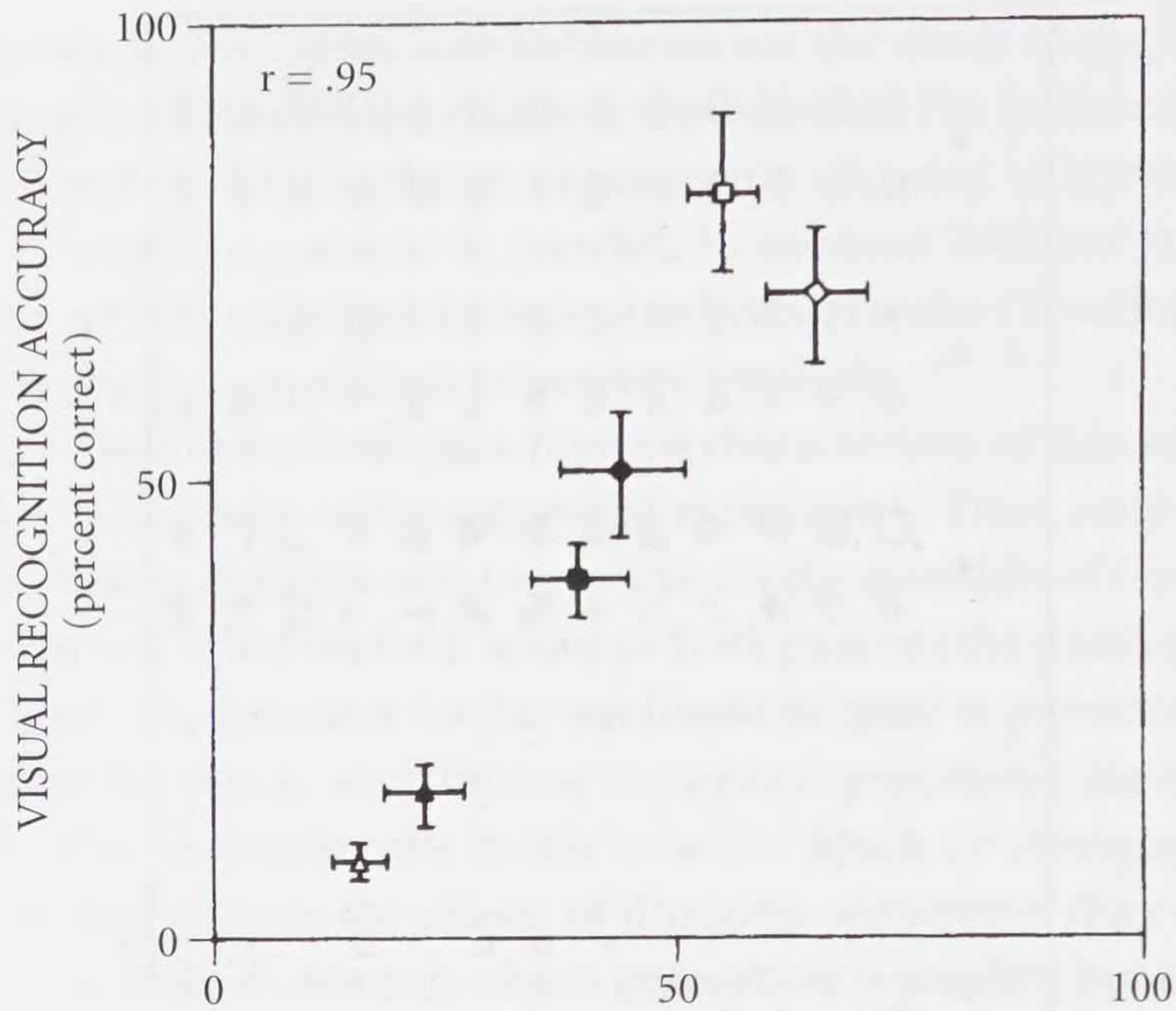


Figure 6. Recognition performance (abscissa haptic and ordinate visual) for the six symbol systems in Figure 5.

taken as strong empirical argument against Georg Berkeley's dogma. At the same time it supports the claim of Gestalt psychologists and Gibsonians that there are perceptual organizing principles independent from sense modalities in the domain of object recognition (Diane Deutsch (1997) reports acoustic illusions in the perception of 'acoustic objects'). James Gibson (1979) has summed up these results in the claim that from the point of view of the perceiver the world of objects does not consist of a multitude of sensations in different modalities but is a unitary percept having systems characteristics. The identification of receptive fields consisting of bi-modal cells, reacting both to visual and to tactual stimulation (Michael Graziano & Charles Gross, 1995), which are invariant against eye-movements show that the parallelism of visual and haptic perception cannot be reduced to an acquired hand-eye-coordination as claimed by activity psychologists (Vladimir Zinchenko and Boris Lomov, 1960).

On the background of these results, George Berkeley's dogma as well as the directly opposed position of visual superiority might be reduced to the same basal assumptions concerning cognition, namely to regard perception as the endproduct of processing sensory information (Hermann v. Helmholtz' 'unconscious inferences') and not taking into account that an organism interacting with objects of the world can only survive if it perceives the **objects: Any** sen-

sor achieving this goal gives the organism with this sensory equipment a better fitness. That in the evolution different sensors for the same physical variables have developed shows that George Berkeley should not have posed the dogma about the priority of touch over vision in object perception but should instead have concentrated on the constraints of the physical environment upon the development of sensors: That is, his 'esse est percipi' would have adressed the question which parts of the physical world demand to exist in the world of the perceiver in order to allow him/her to survive. From a Gestaltist point of view 'being perceived' (percipi) is not accidental but the result of the evolution of perceptual processes timed to the object with interact with the perceiver (Kurt Koffka, 1935).

Notes

1. Why vision and audition seem to be the sensory basis of higher cognitive functions explains John Locke (1694; LI): "No sooner do we hear the Words of a familiar Language pronounced in our Ears, but the *Ideas* corresponding thereto present themselves to our Minds. In the very same instant, the Sound and the Meaning enter the Understanding. So closely are they United, that 'tis not in our Power to keep out the one, except we exclude the other also. We even act in all respects, as tho' we heard the very Thoughts themselves. So likewise, the Secondary *Objects*, or those which are only suggested by Sight, do often more strongly affect us, and are more regarded than the proper *Objects* of that Sense; along with which they enter into the Mind, and with which they have a far more strict and near Connexion, than *Ideas* have with Words. Hence it is, we find it so difficult to discriminate, between the immediate and mediate *Objects* of Sight, and are so prone to attribute to the former, what belongs only to the latter. They are, as it were, most closely twisted, blended, and incorporated together. And the Prejudice is confirm'd, and riveted in our Thoughts, by a long tract of Time, by the use of Language, and want of Reflexion. However, I doubt not, but any one that shall attentively consider what we have already said, and shall say upon this Subject before we have done, (especially if he pursue it in his own Thoughts) may be able to deliver himself from that Prejudice. Sure I am, 'tis worth some Attention, to whoever wou'd understand the true nature of *Vision*."

2. Jerry A. Fodor & Zenon W. Pylyshyn (1981) in their critique of James Gibson's (1979) 'Ecological Perception' have reiterated this position very clearly but without relating it to its Empiristic roots by refuting Gibson's core concept of 'direct perception' with the argument that any theory of perception has to be structured according to transformational grammar.

3. This result shows that the apparent plausibility of the constructivist approach to the perception as suggested by Johannes Müller (1838) or more recently by Michael J. Tarr & Heinrich H. Bülthoff (1995) is not really stringent because the retinotropic projections are not the only information upon which the brain can construct object perceptions.

4. Christian v. Ehrenfels refers directly to Ernst Mach (1886), however similar arguments for the solution of a problem posed by William Molyneux's question appear as early as 1759 when Porterfield argues: "... I have already demonstrated, that the Judgments we form of the Situation and Distance of visual Objects depend not on Custom and Experience, but on an original, connate and immutable Law, to which our Minds have been subjected from the Time they were first united to our Bodies; and therefore the blind Person, immediately upon receiving his Sight, must, by virtue of this Law, by his Eyes alone, without any Assistance from his other Senses, immediately judge of the Situation of all Parts of the Globe and Cube" (pp. 414–415). A similar train of arguments can be found in Immanuel Kant's "Critic of pure reason" (1781) for the visual space as a-priori-representation underlying all other kinds of perception. The first mathematical treatment of perceptual invariants has been gone by Gerhrad Vieth (1818) when constructing the Horopter. Johannes Müller (1838) derived a constructivistic approach for object perception on the foundation of Gerhard Vieth's analyses; he argues that the experience of a rigid body or all other bodies in three dimensions is only possible due to mental activity which constructs this experience from multiple two-dimensional projections when the object or the perceiver in relation to the object is moved (p. 1176); this conception has been revised by Steven Pinker (1997) and Michael Tarr & Heinrich Bülthoff (1995).

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CHAPTER 9

Breaking of continuity in the auditory field

Giovanni Bruno Vicario

1. Stern on continuity

In his almost ignored (and almost unobtainable) *Psychologie der Veränderungsauffassung* (Psychology of perception of change, Breslau 1898[1], 1906[2]), Luis William Stern opened up a field of research never again explored by tackling the problem of continuity in its philosophical and perceptual aspects (pp. 22–28). Considered here are only some parts of his analysis.

Firstly, Stern stresses the fact that in a perceptual continuum, e.g., an even and uninterrupted tone, [1] any fixing of borders or of marks has the character of an arbitrary act, and that because of this possibility [2] the perceptual continuum is a oneness "pregnant" of any multiplicity. I find his examples very impressive: the continuity of time is susceptible to any sort of marking (like Olympiads, *ab Urbe condita*, Christian Era and so on), and can be subdivided *ad libitum* into centuries or milliseconds; the same holds for the continuity of space. Secondly, Stern asserts [3] the difference between the continuity of both time and space, which are the carriers of *all* other continuities, and the continuity of material (perceptual) contents, like sounds in time, colours in space or in time, and the Self only in time.

At this point, Stern writes that [4] "Acts of conscience, by which the material content of a temporal continuum appears as continuous, fall into two categories: perception of persistence or of *constancy*, or perception of *change*. We perceive constancy whenever partial moments, drawn out from the continuum, exhibit equality, or whenever the uninterrupted identity of conscience dominates. By contrast, we perceive change whenever partial moments, drawn out of the continuum, look different, or whenever the identity of conscious content gives rise to the perception of a difference". Then Stern makes the proposal to call [5] "gradualness" that continuity that a certain point leads to a perception of a difference.

Stern formalizes the perception of gradualness in the usual way:

$$a = b;\ b = c;\ c = d;\ d = e;\ e = f;\ f = g$$
$$\text{but } a \neq g.$$

He denies that a succession of judgements of equality takes place in the flow of psychological time, preferring to imagine that we have some sort of covert representation of the relations, not only of each phase with its immediate neighbours, but even with preceding phases. By means of the above mentioned arbitrary conscience act, we make a comparison of *g* with *a*, taking note in some cases of an equality, and in some other cases of a difference. This should be the result of the wandering of attention, which sometimes considers the equality of successive phases and sometimes ranges across the preceding phases to ascertain their difference with respect to the current one. "Where this difference comes from, one cannot know: we only know that in the uninterrupted displaying of phases the relation [of equality between them] never fails, and that no jump or sudden change takes place. This latter is the distinguishing feature of the perception of transition."

Stern continues his analysis by questioning whether the impression of $a \neq g$ takes place on the occurrence of *g*, or later. He argues that at the moment of *g* we may be uncertain about the difference between this phase and *a*, thus leaving the change to unfold: the perception of difference comes afterwards, say at *h* or at *i*, but it is to be referred to *g*. Stern takes advantage of this uncertainty or hesitancy to reaffirm his point on continuity: any breaking of continuity is an arbitrary act, both in order to ascertain an identity and to find out a difference.

2. A short discussion

As far as I know, we have no better individuation of the fundamentals of perceptual continuity than that provided by Stern. Psychological inquiry is nevertheless acquainted with numerous problems related to continuity. Let me point out a few of them.

1. Continuity has much to do with *identity*, in the sense that when something continues, it looks to be identical in all its successive parts. As Stern convincingly shows in a passage of his book (p. 52 ff.), the problem of identity is that we experience identity when something appears to be the same in some attributes, and different in others. It may be difficult to accept this paradox, but things are exactly so. When we listen to a tone which shifts

slightly in frequency, we say that the tone is still the same, *even if* it looks different (that is, lies on a different level of tonal space). When we listen to a tone which on the contrary is steady in frequency, we likewise say that it is the same, but now the difference pertains to the moment of psychological time in which we recognize the sameness. The problem of identity is also analysed in the works of Ternus (1926), Michotte (1950) and Bozzi (1969).

2. Continuity has manifestly to do with the phenomenon of constancies (of size, colour and form), although the classic theory of constancies treats them in terms of an evolution that is supposed, not perceived. In the case of simultaneous comparison (for instance, two vertical bars displayed at different distances, of which we must estimate the length) there is no grounds for continuity, but in the case of successive comparison (first one bar, then the other) something happens that is akin to the perception of an equality or of a difference, as Stern put it. It is worth noting that this sort of comparison incurs the many faults of temporal error (see Vicario, Vidotto and Tomat, 1994a, 1994b) supposedly present even in the perception of continuity or of gradualness. It is also worth noting that in the auditory domain the temporal error is the rule, since comparison between two tones or two noises requires their successive presentation.
3. The perception of continuity forcefully raises the problem of phenomenal time, given that any judgment of sameness is grounded on the check of equality for contents of "moments" that are different only because they are successive. Stern seems to rely mainly on the concept of *Präsenzzeit*, that is on a sort of contemporaneousness among the elements of a succession that allows for comparison, and on the fact that the phenomenal present has "a head and a tail" (James, 1890). Thus the sameness of a sound can be perceived by comparing (so to speak) the features of the sound on the head of the specious present with the features of the sound that are still on the tail of the same present. This can be accepted for the small intervals of physical time across which the phenomenal present ranges, but not for intervals exceeding 1 or 2 seconds. Here the problem is the integrating of successive *Präsenzzeiten*: the psychological inquiry consequent upon the proposal of *quanta* of phenomenal time (Stroud, 1950) fails to find any possible explanation for the fact (see Vicario, 1973; Block, 1990; Incarbone, 1995), and the only reasonable solution at our disposal is the *proteraesthesis* (a sort of mechanism that manufactures the manifold of successive psychological moments, proposed by Brentano (1997; see also Volpi, 1987; and Husserl, 1992).

4. Brentano's and Husserl's analysis of temporal experience shows that the continuity of a phenomenal content is undoubtedly projected into the future, by a mechanism that they call *protension*. This hypothesis has been convincingly borne out by the observations of Michotte (1950), Sampaio (1943) and Burke (1952) and by the screen and tunnel effects. The crux of Brentano's and Husserl's analysis is that the incoming parts of a continuous tone do not appear to be "new" (an aspect also pointed out even by Höffding, 1913; and Wundt, 1902[5]), and that the tone appears as to have existed before we can listen to it (this is the phenomenon of *preceding permanence*, as Michotte calls it). If this interpretation of facts is sound, it follows that the perception of continuity is assured by comparison of the current "impression" not only with past impressions, but also with future ones (whatever this formulation may mean). Otherwise, we must accept the existence of an uninterrupted succession of comparisons between the incoming percept and the immediately precedent one – which Stern explicitly rejects.
5. The definition of perceptual continuity is rather difficult, since it can be applied to basically different stimulus conditions. We may have (a) continuity by steadiness of the stimulus, which is what Stern would call continuity in the strict sense. We can have (b) continuity by continuous change in the stimulus, which is what Stern calls graduality. But we can have also (c) continuity by a sequence of steady-state stimuli to which corresponds the perception of a succession of individual elements: take for instance a chromatic scale, which we perceive as a continuous event even though its elements are perfectly distinguishable steady-state events (the single tones). Involved here is a parts/whole problem, since if we listen to parts we have to recognize their continuity in the proper sense, and if we listen to the whole we have to admit that we experience graduality. (In my study on perceptual events, I classified this case under the heading of *quasi-continuous* events: see Vicario and Zambianchi, 1998.) The problem for Stern's system is that his above mentioned equations can be only applied when the difference between contiguous moments is perceptually non-existent.
6. This brings to a crucial aspect of the perception of change. When we look at the seconds-hand of a clock, we see its movement; on the contrary, when we look at the minutes-hand we cannot see any movement (despite its physical motion). What surprisingly occurs, in the second case, is that from time to time we see that the hand looks displaced forward, but we cannot catch it in the act of moving, despite the closest focusing of attention. In other words, we do not see any movement, but we *recognize* that a

displacement has occurred. (I use the verb "to recognize" because we cannot perceive any movement in real time: we simply take note of an event just after its completion.) This is the case to which Stern's equations are to be applied, but I see nothing arbitrary in that sudden displacement, if by "arbitrary" we mean "at the will of the observer". The displacement suddenly springs out of the situation, in an unexpected way, and cannot be forestalled or postponed at the discretion of the perceiver.

7. The breaking of continuity strikes me of great importance in the search for a definition of continuity itself. Stern devotes many pages (29–47) to the perception of a breaking of continuity in the form of a sudden transition (*Übergangswahrnehmung*) between a percept endowed with some characteristics and a percept where one characteristic is suddenly changed (brightness for surfaces, intensity for tones). However, it is not clear which continuity is at issue, in that we have continuity of the object that changes in just one of its perceptual aspects, and a breaking of continuity for the aspect that has changed. (The German noun *Stetigkeit* unfortunately carries both meanings: continuity and permanence.) This distinction is instead very clear in Michotte (1950), who speaks of *permanence* when we have continuity of the object, and of *substitution* when we do not have continuity either of a characteristic of the object or of the object itself. Suppose we have a white disc on the monitor, and that we replace it with a bigger or smaller disc (change in size); with a red disc of the same size (change in colour); or with a white square of the same size and colour (change in form). We will see the permanence of the object and the change of the characteristic in question. But if we change all three characteristics at the same time – says Michotte – we will see the substitution of the object with another one.

The discussion of the matter by Stern and Michotte is very interesting, but it is evident that they lack empirical observations, and that the laboratory facilities which we now enjoy (graphic computers for visual stimulation, synthesizers for auditory stimulation) allow us to create experimental situations that were not possible in the past. This is the line of inquiry pursued, for instance, by research on the perception of transition in brightness (Vicario and Zambianchi, 1996), the perception of a stop in the motion of an object (Saltini, 1995) or the point of a change in velocity of a moving point (Colombo, 1997). As to the perception of change in the auditory field, already Stern pointed out the differences between the two sensory modalities (vision and audition). These differences constitute a labyrinth of phenomena that should be first explored individually, waiting for a sen-

sible connection of facts to arise. In the visual field, for instance, a change of place gives rise to (stroboscopic) motion, while in the auditory field a change in tonal space gives rise to the succession of two tones. In visual field a change in brightness leaves the object unaffected, where in auditory field the succession of two tones of the same tonal height, the first at low loudness and the second at high loudness, sometimes gives rise to a substitution, sometimes to the amodal presence of the faint tone beneath the louder one (see Vicario, 1960). In the perception of continuity of change in brightness, obtained by means of sequences of short stimuli of steady luminance, perfect continuity of brightening (or of darkening, see Vicario and Zambianchi, 1998) can be reached for lengths of the steps (60 msec) that never could give rise, in the tonal domain, to the perception of a perfectly continuous shifting of frequency: in the tonal domain we would only hear a very fast succession of individual tones, in the form of a *glissando*.

8. Among the many kinds of breaking of a continuity, we have the *creation* and the *annihilation*, investigated by Michotte and his collaborators (1962). They studied creation and annihilation as phenomenal counterexamples of the main problems at issue, those of preceding permanence and succeeding permanence, and they tried to establish the stimulus conditions for each kind of percept. In their examples, however, the breaking of continuity is not that of the object, but that of the ground: a light is switched on in the dark, coming into existence and dispelling the darkness; or it is switched off, annulling itself and restoring the darkness; a noise suddenly appears in the silence, making the silence stop existing (better, pushing it into the background), or a noise suddenly ceases, making the silence to reappear (better, moving it into the foreground). This is a relation between continuity/interruption and figure/ground still to be investigated, although it was recognized by Michotte (1950). The mere fact that an object or an event begins or ceases to exist on the phenomenal scene is intriguing, since there is much evidence that the borders of events (as I call them) that evolve in a uniform way are different from their central parts. I refer to the Fröhlich effect (1929: a moving object that suddenly appears in the field is seen to initiate its path considerably "after" the point where it actually appears) and to the Runeson effect (1974: a point that moves with uniform velocity appears to be accelerated in the first fraction of its motion). I have tried to transpose the Frölich effect from the perception of movement in space to the perception of "movement" in the evolution of brightness for an object that brightens or darkens on a ground of steady luminance. I found that the perceived value of brightness of the object at

the beginning (or at the end) of evolution does not depend on the actual luminance of the stimulus at the beginning (or at the end) of the physical event, but on the relation between the brightness of the object at the beginning (or at the end) of perceptual event and the brightness of the ground (Orlandi, 1998). I obtained a similar effect with discs that continuously change in diameter as they expand or contract, in expansion or contraction: we can never see their actual size at the beginning or at the end of evolution (paper to be published). Effects of the same kind are observable in other situations (see Actis Grosso, Stucchi and Vicario, 1996; Vicario and Actis Grosso, 1997).

3. The problem of unnoticed change

As said above, the problem of continuity, as for its perceptual aspects, is a tangle of not clearly related facts that is difficult to unravel. It is advisable to go in search of new facts that can shed light on at least some aspects of the problem.

Take for instance the case of the minutes-hand on a watch. Apart from the formalization given by Stern to the problem, what makes me recognize that the last phase of an evolution has something different from the initial one, despite the fact that in no phase after the first have I been able to perceive any else change? I should set forth two conjectures.

A. The difference between the second phase and the first (between the third and the second, the fourth and the third, *etc.*) is below the threshold, and I cannot perceive it; nevertheless the sensory system takes note of that difference, and saves it. The single differences are cumulated, and when the amount exceeds a certain value, it is discharged on the first available phase, so that we have the sudden impression that something has changed because the discharged amount pushes the difference above the threshold. The continuity is broken.
B. The value assumed by the characteristic at issue in the first phase is saved by the perceptual system. The value of that characteristic in the following phases is time by time compared with the value of the first until the differential threshold is reached. At this point we see the break of continuity.

I am perfectly aware that nothing imaginable corresponds to the term "phase". According to phenomenological method as applied to perceptual phenomena, I should not speak of anything that does not have phenomenal existence, and in the perception of continuity there is no place for perceptible phases. In ad-

dition, I can speak of phases only if I have a theory about their integration, which I do not offer. Nevertheless, as we shall see later, the two conjectures are not devoid of phenomenological sense. Therefore my problem was to find another situation comparable with that of the hand of the clock by which the two conjectures could be tested. I resorted to the auditory field, and to a special kind of continuity, that of diatonic scales. The experiment was performed by Massimo Grassi (1996), a final-year student in the Faculty of Psychology of Padua University.

4. Mistuned scales

Let us consider an ascending diatonic scale, where the interval between succeeding tones is a bit more or a bit less than the due one (taking for semitones intervals of 101, 102, 103 ... or of 99, 98, 97 ... cents respectively). At which point of the scale does the observer become aware that the scale is mistuned? What a sort of experience is the perception (recognition) that the tonic has changed?

Grassi prepared a set of scales according to the experimental design illustrated in Figure 1.

According to the design, 20 altered scales were to be tested, 10 of them ascending and 10 descending. 2 tempered scales, 1 ascending and 1 descending, were added. The duration of each tone was 1 sec. A first group of subjects consisted of 25 experienced musicians; a second group of 25 undergraduate students of psychology (see Grassi, 1996 for details). The method was to ask the subjects to interrupt the scales when they felt that they were mistuned; the time elapsed between the beginning of the scale and the moment of interruption was chosen as dependent variable.

MAJOR DIATONIC SCALES

ASCENDING		DESCENDING	
intervals		intervals	
LONGER	SHORTER	LONGER	SHORTER

long semitones: +1, 3, 5, 7, 9 cents
short semitones: –1, 3, 5, 7, 9 cents

Figure 1. Design of Grassi's experiment (1996).

The quantitative results are summarized in the two graphs of Figure 2, where the interruption times are plotted against the sign and the amount of mistuning.

It is worth noting that introspective reports of some subjects of Grassi's experiment relate the question raised by Stern, as to the moment at which the difference between the last and the first phase arises. Stern argues that the difference may be initially uncertain, and that the perceiver may let it grow until it becomes indubitable. This is what actually happens, in fact, but it depends on the tendency of subjects to underestimate or overestimate their impressions: a personality trait found in all research on perception where a judgment is required. I have encountered the same problem in the perception of hardly distinguishable visual events (Vicario, 1992), since experimental subjects can be divided into two categories: those who give priority to quickness of reaction and the others who give priority to the precision of responses. (Also to be taken into account is reaction time: about 200 msec or more.) In the case of Grassi's scales, the subject almost invariably waited for the next grade before pressing the key. Decision time in this sort of task is of much importance, and it must be considered whenever we make use of the psychophysical method of limits. Another outcome of the experiment, a quite unexpected one, was that the perfectly tuned scale is not the "well-tempered" one by which semitones count exactly 100 cents, but a scale made up by semitones that count about 101 cents (only for musicians in ascending scales, but even for naïve subjects too, in descending scales). This gainsays theories that ground pitch perception and consonance on mathematical or physical ratios.

Grassi's experiment seems give support to hypothesis (B), in the sense that experimental subjects interrupt the developing scale when it becomes inconsistent with the tonic given by the first tone. But closer inspection of the two cases, that of mistuned scales and that of the moving hand of the watch, shows that they are not entirely comparable. They have something in common, in that the first phase of the succession has in both cases a perceptual or cognitive existence: we continue to perceive the first position on the watch, and in mistuned scales the first position is always psychologically present as the tonic. From another point of view, however, the two situations are quite different: the unceasing change of position in the case of the watch is unnoticeable, whereas in that of the scales the change in pitch of each successive tone is perfectly perceived. Grassi performed another experiment (on suggestion by Paolo Bozzi and not yet published), where the scales were presented accompanied by a tonic played two octaves below or above the range of the scales. The interruptions took place at about the same moments, which means that the tonic (the first position in

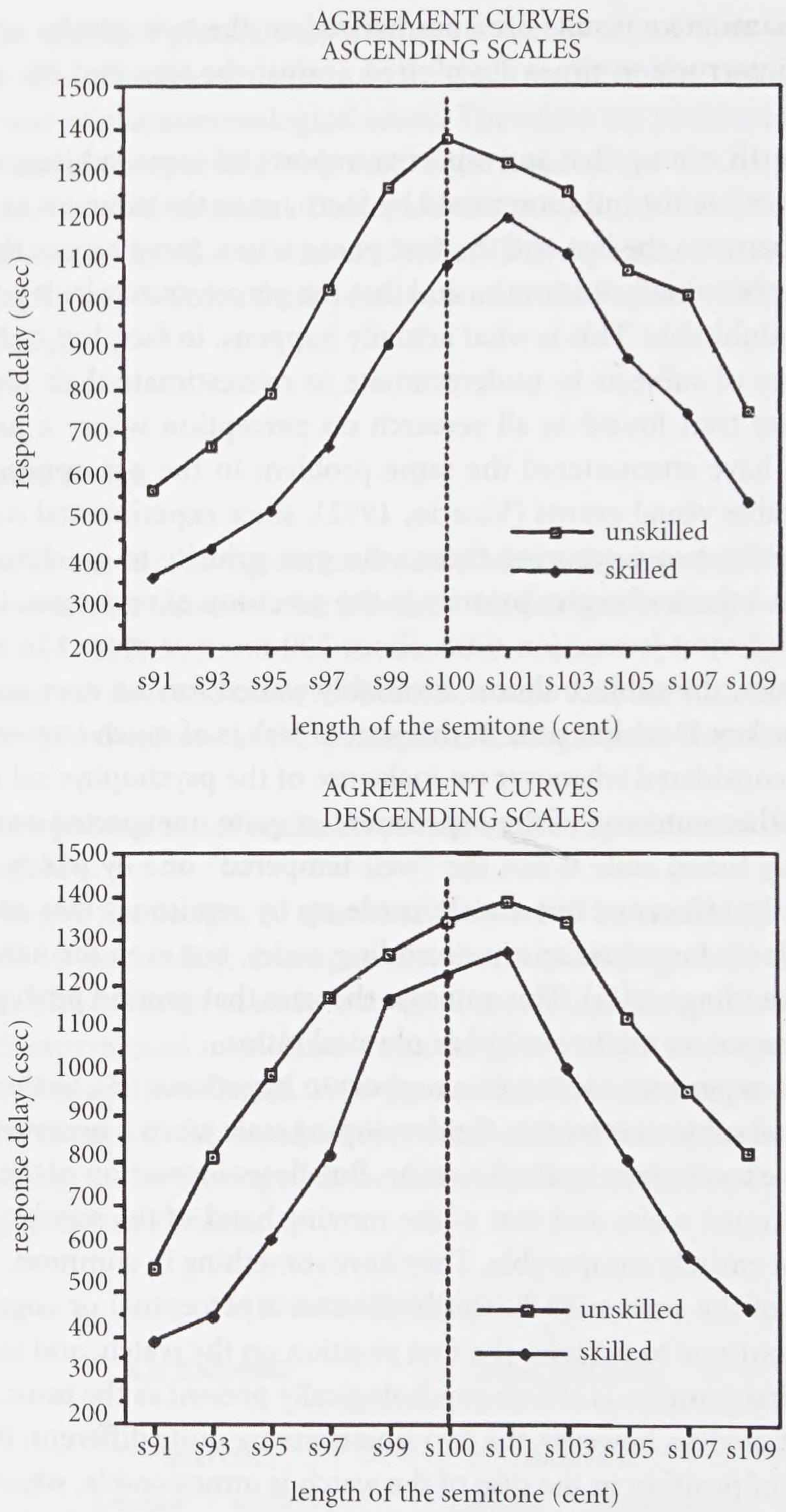

Figure 2. Outcomes of Grassi's experiment (1996). On top: interruption times for the ascending scales (in csec, from the beginning of the scales, on the ordinate) plotted against the length of semitones (in cents; 100 cent = tempered semitone, on the abscissa). At bottom: the same for descending scales.

tonal space) does not clarify the case, or that the tonic is a cognitive frame of reference devoid of any perceptual content.

In short, Grassi's experiment did not resolve the question concerning the two hypothesis formulated earlier. But at least it showed that some explanations are simplistic, and that more facts must be collected before any theoretical conclusion can be drawn.

5. Breaking of continuity in the perception of rhythm

The most surprising aspect of Grassi's experiment was the asymmetry of thresholds in the breaking of the continuity: we become aware first of a shortening of semitones, and then of a lengthening of them. Otherwise, we become aware first of the contraction of the scales in tonal space, and then of their expansion, with an asymmetry that is statistically significant. I therefore decided to test another type of continuity in tonal domain, in order to ascertain whether its breaking shows the same kind of asymmetry.

I asked the final-year student Davide Cordioli (1998) to determine the thresholds for the perception of acceleration and deceleration in a rhythm. Cordioli exposed his experimental subjects to 8 very short tones, which in the constant condition [C] were 1 sec apart. In the accelerated versions [A] the interstimulus interval decreased by a fixed rate at each stroke (6 values, ranging from 0.6 to 2.7%). In the decelerated versions [D] the interstimulus interval grew by a fixed rate at each stroke (same 6 values). 30 subjects judged 25 experimental situations, administered with constant stimuli method, and were asked to assign each rhythm to the following categories: constant, accelerated, slowing down.

The quantitative results are summarized in the graphs of Figure 3. Shown on top is the distribution of the judgements in the three categories (on the ordinate the percentages of judgements, on the abscissa the per cent deviations from the value of 1 sec). At bottom is the comparison between the curve of the judgements of acceleration and that of the judgements of deceleration.

As one can see, the threshold for the judgement of acceleration is situated around a shortening of the 1 sec interval by –0.75%, whereas the threshold for the judgement of deceleration is situated around a lengthening of the 1 sec interval by +0.9%. The difference is very small in absolute terms, but it should be borne in mind that the estimation of rhythm is one of the most accurate performances of the human subject; anyway, it is statistically significant. The

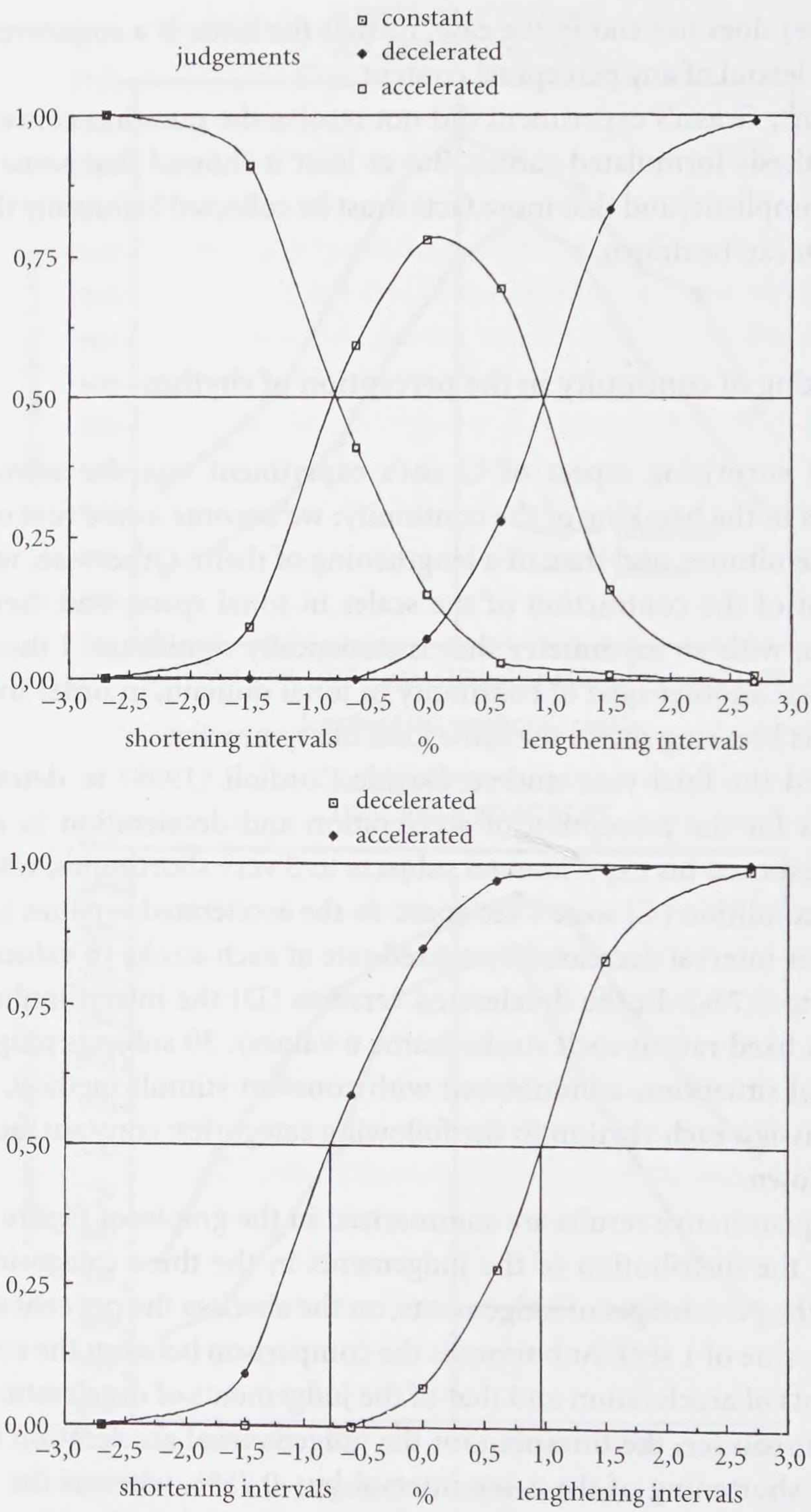

Figure 3. Outcomes of Cordioli's experiment (1998). On top: probability of the three judgements (constant, slowed down, accelerated) plotted against the percent rate of change in interstroke interval. At bottom: psychometric functions of acceleration (left) and of slowing down (right) successions. The two thresholds are indicated.

conclusion should be that, as regards rhythms as well, there is an asymmetry in the power of discrimination for changing events.

In fact, the results of Cordioli's experiment are only indicative that something strange occurs this sort of task. The only 1 sec interstimulus interval was tested, and it is impossible to say whether the difference that emerged grows or disappears with faster or slower rhythms. (Another final-year student, Chiara Cadei, 1998, ascertained that with interstimulus intervals of 2, 3 and 6 seconds the difference disappears.) There is also a difference of methods: Grassi asked for a motor response during the exposition of the stimulus, Cordioli asked for a categorization after the stimulus was exposed. Were Cordioli's findings confirmed by other experiments, the question would arise as to the comparability of jumps in tonal space and jumps in subjective time. Another difference is that in the case of scales there is a content that physically and phenomenally changes, whereas in the case of rhythms the "phases" are devoid of any sensory content. We may say that intervals between strokes are filled by phenomenal time or phenomenal duration, but we cannot go beyond this statement. The point is of importance, given that in mistuned scales the ratio between two succeeding intervals is always the same, where in accelerating or decelerating rhythms the ratio is ever different (in Grassi's experiment, the tonal distance between two successive grades is ever the same, whereas in Cordioli's experiment the temporal distance between two successive strokes is always different).

To sum up, Cordioli's experiment, like Grassi's, raises more issues than that it was devised to clarify. It is apparent that where Grassi's succeeding tones have a perceptual content, on the registration of which one can speculate, Cordioli's interstroke intervals have no perceptual content. To suppose that in some niche of the "computational mind" (Jackendoff, 1987) complex comparisons take place between durations is nothing but a *bon mot*, since there are no means to verify the conjecture.

6. Concluding remarks

I think that [1] the general problem of continuity stressed by Stern is of overriding and at the same time neglected importance both for philosophy and science. Perhaps Popper (1998, n. 7) was right when he said that is extremely hard to convince scientists that the world we face is not made up of things that change, but of change itself. In the second place, I must admit that [2] it is difficult to have a well-founded opinion on continuity because its roots are the

controversial terrain of the nature of time (see Vicario, 1997); as regards our problem, we do not know whether continuity is a subjective or objective mark of change. I also feel that [3] ordinary logic, in this sort of question, breaks down (this also happens in quantum mechanics: see Albert, 2000, p. 29; also Vicario, 2001, §28), so that it is better to stick to the facts, and forget logic (see Metzger, 1971). From this point of view, [4] experimental psychology may be of some use, especially if the continuity is of subjective nature. More specifically, [5] auditory perception seems to be the most fruitful source of cues that can clarify the problem of continuity, since auditory events are not affected by the unmanageable dimensions of visual events (form, colour, third dimension, *et cetera*).

Grassi's and Cordioli's experiments do not settle the question of whether the breaking of continuity is due to an accumulation of differences that becomes unbearable and eventually gives rise to the perception of a change, or to a sequence of comparisons with preceding phases that at a certain point surpasses the threshold of just noticeable difference.

It is, however, incontrovertible that as soon as the first tone is heard, the tonic is established too, and that the presence of the tonic accompanies all the subsequent tones, even if it is difficult to say whether this tonic is amodally present like the ground behind a figure, or whether it acts as a categorial or cognitive platform on which the succession of tones develops. One cannot deny that the existence of the tonic during the whole development of change can offer the ground for the comparison of the current auditory content with the first phase of the whole event, thereby verifying the conjecture (A). In this sense, the sudden perception of the mistuning should correspond to the abandonment of the tonal platform just created, and to the boarding of another tonal platform. There is, however, a suspicion that this is not the case: when the tonic is present in every grade of the scale, the threshold of mistuning does not change (even within the limits of Grassi's observations on a group of untrained subjects). The other conjecture (B) thus contributes to explanation of the phenomenon: the breaking of the continuity of the tonic should be ascribed to an accumulation of differences that eventually makes itself to be felt.

In my opinion, mere establishment of the fact that there is asymmetry in the breaking of continuity, for successions by which some thing increases, and by which the same thing decreases, could be of considerable value in a field of research where we know almost nothing. This can be encapsulated by saying that the living being is not interested in the sort of continuity that is steadiness, but in change, which provides more opportunities for survival, but this is mere speculation. No conjecture can be advanced about the better discrimi-

nation of decreasing mode as compared with the increasing mode (scales with "shorter" semitones are more easily recognized than that with "longer" ones; rhythms where the strokes are spaced by shorter intervals are recognized more easily than those spaced by longer intervals), no conjecture can be advanced. Whether this difference concerns a general feature of perception of change, as I suspect to be the case, is again matter of experimental inquiry. For instance, take a staircase where the elevation of steps increases (decreases) by 0.5 cm at each step: will the walking subject become aware of something wrong when going upstairs or downstairs?

Acknowledgment

I am indebted with prof. Serena Cattaruzza Derossi (University of Trieste) for having reviewed my translations of Stern's text.

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CHAPTER 10

The limits of continuity

Discreteness in cognitive semantics

Ronald W. Langacker

I take it as being evident that many aspects of language structure are matters of degree. This is a common theme in both functional and cognitive linguistics, including my own work in **cognitive grammar** (Langacker, 1987a, 1990, 1991, 1999a). It would however be simplistic to assume that a commitment to cognitive (as opposed to formal) semantics necessarily correlates with the view that semantic structure is predominantly continuous (rather than discrete). I suspect, in fact, that the role of true continuity in linguistic semantics is rather limited. My goals here are to clarify some of the issues involved, to briefly discuss a certain amount of data, and to propose a basic generalization concerning the distribution of discrete vs. continuous phenomena.

In approaching these matters, I will ignore the fact that linguistic structure reduces, ultimately, to the activity of discrete neurons that fire in discrete pulses. Our concern is rather with phenomena that emerge from such activity at higher levels of organization, phenomena that could in principle be either discrete or continuous. I will also leave aside two aspects of discreteness that are too obvious and general to merit extended discussion: the fact that we code our experience primarily by means of discrete lexical items, each of which evokes individually only a limited portion of the overall notion we wish to express; and the discrete nature of the choice (i.e. at a given position we have to choose either one lexical item or another, not some mixture or in-between option).

In using terms like **discrete** and **continuous**, what exactly do I mean? A continuous parameter has the property that, between any two values (however close), an intermediate value can always be found. There are no "gaps" along the parameter, nor any specific values linked in relationships of immediate succession. By contrast, discreteness implies a direct "jump" between two distinct values, one of which is nonetheless the immediate successor of the other. To

take an obvious example, the real numbers form a continuous series, whereas the integers are discrete (there is no integer between 4 and 5). Many continuous parameters are of course discernible in conceptualization and linguistic semantics: length, pitch, brightness, the angle at which two lines intersect, etc. Yet the role of true continuity appears to be circumscribed in various ways.

We must first distinguish actual continuity from other phenomena that tend to be confused with it. One thing that does not qualify as continuity is hesitancy or indeterminacy in the choice between two discrete options (which is not to deny that one's inclination to choose a particular option may be a matter of degree). For instance, although I may not know whether to call a certain object a *cup* or a *mug*, I nevertheless employ distinct and discretely different prototypical conceptions in making the judgment (cf. Wierzbicka, 1984). Continuity is also not the same as vagueness or "fuzziness". It would be arbitrary, for example, to draw a specific line as the definitive boundary of a *shoulder*. This body part is only fuzzily bounded – there is no definite point at which it is necessarily thought of as ending. Yet we do conceive of it as a bounded region (this makes *shoulder* a count noun), and a boundary implies discontinuity (a "jump" between shoulder and non-shoulder). We impose the boundary despite being unsure or flexible in regard to its placement.

I believe, moreover, that certain linguistic phenomena often thought of as forming a continuum are better analyzed in terms of multiple discrete factors that intersect to yield a finely articulated range of possibilities. For instance, basic grammatical categories are sometimes seen as varying continuously ("squishily") between the two extremities anchored by nouns and verbs (Ross, 1972). I have argued, however, that grammatical classes are definable on the basis of discrete semantic properties (Langacker, 1987a, part II; 1987b). A noun designates a **thing** (defined abstractly as a "region"), while an adjective, preposition, participle, infinitive, or verb designates a **relation**. Verbs are **temporal** (in the sense of designating relationships that evolve through time and are scanned sequentially), whereas the other categories are **atemporal** (being viewed holistically). Some relations are **simple** (i.e. they comprise just a single configuration), but others – verbs, infinitives, as well as certain participles and prepositions – are **complex** (comprising multiple configurations). When additional semantic traits are taken into account, together with polysemy and the prototype organization of individual categories, behavior can be anticipated that is "squishy" for all intents and purposes. Still, merely indicating the position of elements along a continuous scale can at best only *summarize* their behavior. Specific semantic characterizations offer the prospect of *explaining* it.

Let us turn now to conceptual parameters that can indeed be regarded as continuous. Even here there are serious qualifications. The most obvious point is that a continuous scale is usually not coded linguistically in a continuous manner. For temperature we have terms like *hot*, *cold*, *warm*, *cool*, *scalding*, and *freezing*, not to mention ways of expressing specific values (e.g. *13° C.*). We devise musical scales to structure the domain of pitch, and for time we have many discrete units of segmentation and measurement. The most celebrated example, of course, is the idiosyncratic "tiling" of color space imposed by the basic color terms of each language. Color is also celebrated as a domain which harbors a certain kind of discreteness despite the apparent continuity of its basic dimensions. I refer to the phenomenon of "focal colors", which provide the prototypical values of basic color terms and have special cognitive salience even when such a term is lacking (Berlin and Kay, 1969; Kay and McDaniel, 1978). Focal colors mitigate the continuity of color space by making it "lumpy" rather than strictly homogeneous. As natural cognitive **reference points**, the lumps are easily adopted as the basis for categorizing judgments, so that color categories tend to coalesce around them.

Focal colors are just one manifestation of a reference-point ability that I have claimed to be both ubiquitous and fundamental in cognition and linguistic semantics (Langacker, 1991, 1993b, 1995). It is, I think, self-evident that we are able to evoke the conception of one entity for purposes of establishing "mental contact" with another. This reference-point ability is manifested in the physical/perceptual domain whenever we search for one object in order to find another, as reflected in sentences like the following:

(1) a. *The drugstore is next to the post office.*
b. *There's a deer on that hill just above the large boulder.*

More abstractly, a reference-point relationship is central to the meaning of "possessives": *the man's wallet*; *my cousin*; *the girl's shoulder*; *our train*; *her attitude*; *your situation*; *Kennedy's assassination*; etc. I suggest, in fact, that it constitutes the one constant aspect of their meaning. This **schematic** semantic value accounts for both the extraordinary variety of the relationships coded by possessive elements and also their *asymmetry*. If the "possessor" is properly analyzed as a natural cognitive reference point vis-à-vis the "possessed", it stands to reason that these roles would not in general be freely reversible (**the wallet's man*; **the shoulder's girl*; **the assassination's Kennedy*).

With respect to basically continuous parameters, the reference-point ability has what might be termed a "quantizing" effect. We are not in general able to directly ascertain a precise value falling at an arbitrary location along a con-

tinuous scale, nor do languages provide separate terms for each possible value. Instead, the usual strategy is either to assimilate the value to a salient reference point (ignoring its deviation therefrom), or else to estimate and discretely characterize its position in relation to one or more such reference points. The result is a kind of quantization, wherein linguistically coded values either "jump" directly from one reference point to another, or alternatively, are calculated from reference points in some discrete fashion.

Quantization is most apparent when a continuous parameter is structured by means of a discrete grid or numerical scale. The musical scale is a case in point. Not only do the basic terms (*C*, *D*, *E*, etc.) jump from one precise value to the next, but they also provide the basis – both conceptual and linguistic – for determining the only permissible intermediate values. Conceptually, *F-sharp* or *B-flat* lies mid way between two primary values (or else one quantum above or below such a value, given some conception of the magnitude of allowable increments/decrements). Linguistically, the expression that codes an intermediate value comprises the basic term and either of two discrete qualifiers (*sharp/flat*). A temperature scale is comparable except that there is more flexibility in specifying intermediate values. In describing the temperature as being *13.2° C.*, we take 13° C. as a reference point and indicate that the actual value lies beyond it at a distance representing a certain fraction of the interval between 13° and 14°. And while it is true in principle that any real number can be used to specify a temperature, in everyday practice we confine ourselves to the integers or at most to fractional intermediate values that we can estimate in terms of quanta. Intuitively, for instance, I understand 13.2° as a step beyond 13° such that five steps of the same magnitude would take me to 14°.

Fractions themselves neatly illustrate the type of phenomenon I have in mind. Expressions like *2* ½ and *5* ¾ clearly take the integers as both linguistic and conceptual reference points. Moreover, they use other integers as the basis for computing a specific intermediate position: the denominator indicates how many steps there are between two successive integers, while the numerator specifies how many steps should be taken. Or consider the angle at which two lines intersect. Although there is obviously a continuous range of possible values, it seems evident that certain discretely computed values have special cognitive status. Particularly salient is an angle of 90°, as reflected by terms like *right angle* and *perpendicular*. The reason, I suggest, is that perpendicularity represents the privileged situation in which the two angles formed by one line joining another have precisely the same magnitude – if one angle is mentally superimposed on the other (which is thus invoked as a kind of reference point), they are found to coincide. We are also more likely to characterize an angle as

being *45°*, *30°*, or *60°* than, say, as *7°*, *52°*, or *119°*. These values are privileged psychologically because they bear easily computed relationships to a right angle. An angle of 45° is one whose complement within a right angle is identical to it in magnitude. As for 30° and 60°, we can easily imagine sweeping through a right angle in three discrete and equal steps, defining three component angles whose superimposition likewise results in judgments of identity.

Quantization of this sort is by no means confined to quasi-mathematical domains. For instance, compound color expressions like *brick red*, *celery green*, and *sky blue* can be thought of as evoking dual cognitive reference points. By itself, a term like *red*, *green*, or *blue* evokes a focal color, which in turn evokes the more inclusive region in color space that it anchors. A noun such as *brick*, *celery*, or *sky* names an entity that not only has a characteristic color but is sufficiently familiar to serve as a reference point. From these two reference points, we compute the proper notion: *red* tells us that *brick* is to be construed with respect to its color, and *brick* directs our attention to a particular location within the *red* region.

Also varying continuously are parameters such as size, length, and distance. We can of course measure these numerically, as for temperature. The more usual strategy, however, is to assess magnitudes only with respect to broad categories standing in binary opposition: *big* vs. *small*; *long* vs. *short*; *near* vs. *far*. The categorization is therefore basically discrete despite the vagueness of the boundaries. (Continuous analogical coding – as in *The train was looooong* – is clearly a rather marginal phenomenon.) Furthermore, placing an object in such a category involves a single step, in either a positive or a negative direction, from a privileged value that serves as reference point for this purpose. For a given object type, that reference point comprises the range of values that everyday experience has led us to regard as being "normal" for that type. Thus a *big flea* is smaller in absolute terms than a *small moth*, and a *short train* is longer than a *long centipede*.

The phenomenon is quite general. It seems to me that in every domain we operate primarily in terms of salient reference points, from which we arrive at other notions in ways that are largely discrete. When the effect of reference points and quantization is worked out systematically and fully appreciated, the role of true continuity in linguistic meaning will, I believe, appear rather limited. This is not to say that it has no role whatever. There are in fact important aspects of linguistic semantics for which continuity should probably be considered the default assumption. Let me offer the following broad generalization as a working hypothesis that may have some heuristic value: *with respect to the "internal structure" of a linguistically coded conception, discreteness*

predominates; on the other hand, semantic effects due to "external" factors – i.e. relationships with other conceptual structures – are basically continuous.

Since conceptions are containers only by dint of metaphor (and are not really very container-like), the terms "internal" and "external" should neither be taken as implying a strict dichotomy nor pushed beyond the limits of their utility. Factors reasonably considered internal are an expression's conceptual "content" and many facets of its "construal". I have thus far focused on content, arguing that true continuity is circumscribed and circumvented in various ways. **Construal** is the phenomenon whereby essentially the same content is susceptible to alternate "viewings", which represent distinct linguistic meanings. One aspect of construal, namely **background**, is by nature an external factor. Other, more internal aspects include **specificity**, **scope**, **perspective**, and **prominence**. Here, as with content, the role of true continuity is more limited than one might think.

Specificity (or conversely, **schematicity**) refers to our manifest ability to conceive and portray a situation at any level of precision and detail, as exemplified in (2):

(2) *Something happened. > A person saw an animal. > A woman examined a snake. > A tall young woman carefully scrutinized a small cobra.*

Observe, however, that we can generally only adjust the level of specificity in quantized fashion, either by adding a discrete element (*woman > young woman*) or else by shifting from one discrete level to another in a taxonomic hierarchy (*examine > scrutinize*). Furthermore, beyond their obvious discreteness such hierarchies are usually "lumpy", in that certain levels have greater cognitive salience than others. In particular, the "basic level" (e.g. *snake* in the hierarchy *thing > animal > reptile > snake > cobra*) is known to have special psychological status (Rosch, 1978).

I define an expression's **scope** as the array of conceptual content it invokes and relies upon for its characterization. By nature, it tends to be flexible and variable – it is generally no easier to precisely delimit an expression's scope than it is to determine exactly how far a shoulder extends. Nevertheless, there is good linguistic evidence for believing not only that this construct has some kind of cognitive reality, but also that scopes are conceived as being bounded, however fuzzily (see Langacker, 1993a). Grammatical constructions can refer to them specifically and equate them with other bounded regions. Consider the "nested locative" construction, as in (3):

(3) *The camera is upstairs in the bedroom in the closet on the top shelf.*

Intuitively, this construction involves a "zooming in" effect, wherein each successive locative in the sequence focuses on a smaller area contained within the previous one. More technically, we can say that the scope for interpreting each locative in the sequence is limited to the *search domain* of the preceding locative. (The search domain of a locative is defined as the area to which it confines the entity being located, i.e. the set of locations that will satisfy its specifications.) A partonomy like *arm* > *hand* > *finger* > *knuckle* further illustrates both nesting and quantization with respect to scope: the conception of an arm overall provides the spatial scope for the characterization of *hand*; the conception of a hand in turn constitutes the immediate spatial scope for *finger*; and that of a finger, for *knuckle*.

The term **perspective** subsumes more specific aspects of construal such as **vantage point**, **orientation**, direction of **mental scanning**, and **subjectivity/objectivity**. Although some of these factors can in principle vary continuously, in practice they tend toward discreteness. Presumably, for instance, our conception of a *cat* includes numerous visual images, representing cats with different markings, in various postures, engaged in certain activities, etc. There is doubtless considerable variation and flexibility. Still, it seems apparent that these images tend to reflect certain canonical vantage points, and certain orientations of the cat within the visual field. These vantage points and orientations are of course those which predominate in our everyday visual experience. For example, images in which the cat is viewed from underneath, or is upside down within the visual field, are possible but hardly typical.

The notion of **mental scanning** can be illustrated by the contrast between pairs of expressions like the following:

(4) a. *The roof slopes steeply {upward/downward}.*
b. *The road {widens/narrows} just outside of town.*
c. *The hill gently {rises from/falls to} the bank of the river.*

In each case a difference in meaning is quite evident, even though the two expressions describe precisely the same objective situation. Intuitively, moreover, the semantic contrast involves *directionality*, even though the situations described are static – objectively, nothing moves, hence there is no apparent basis for directionality. I do ascribe motion to these sentences, but not on the part of the subject: rather, it is the *conceptualizer* who "moves" in these expressions, scanning mentally through the scene in one direction or the other (Langacker, 1990, Ch. 5). For our purposes, the pertinent observation is that the contrast in directionality (e.g. between the conceptualizer scanning *upward* along the roof or *downward*) is clearly discrete.

Subjectivity/objectivity is defined as the extent to which an entity is construed, asymmetrically, as the "subject" vs. the "object" of conception (Langacker, 1985; 1990, Ch. 12). In (4), for example, both the conceptualizer and his motion are construed *subjectively*, since the conceptualizer does not actually conceive of himself as scanning mentally through the scene, but merely does so implicitly as he focuses on the *objective* configuration thus assessed. Although subjectivity/objectivity is a matter of degree, here too there are grounds for believing that the scale is lumpy and partially quantized owing to the privileged status of certain canonical arrangements. Consider the role of the speaker, for instance. At one extreme, represented by the pronoun *I*, the speaker goes "onstage" to be the expression's referent; as the explicit focus of attention, the speaker is construed quite objectively. Another standard arrangement finds the speaker "offstage" but still within an expression's scope, hence intermediate in terms of subjectivity/objectivity. Examples include deictics (e.g. *this*; *here*; *now*) and sentences like (5), where the speaker functions as the default-case reference point.

(5) *Please come as soon as you can.*

The last basic option is for the speaker to remain outside an expression's scope altogether, having no role in the conception conveyed apart from the *conceptualizer* role itself (which he has in every expression). In this event the speaker's construal is maximally subjective.

There are many sorts of **prominence**, and while some kind of quantization may in each case be discernible, I suspect that in general it may be less obvious and less important in this area. Nonetheless, the two kinds of prominence that are most essential for grammatical purposes show definite quantum effects. One type is **profiling**, which might be characterized as "reference within a conceptualization". Within its scope (i.e. the conceptual content it invokes), every expression profiles (designates) some substructure. Thus *knuckle* profiles a certain substructure within the conception of a finger, and *finger* within the conception of a hand. Many expressions (verbs, adjectives, prepositions, adverbs, etc.) profile **relationships**. For example, *conquer* designates a two-participant relationship that evolves through time, whereas the stative-adjectival *conquered* profiles the final resultant state of that process. (*Conqueror* profiles a **thing**, namely the agentive participant of *conquer*.) Even though an expression's profile is not invariably susceptible to precise delimitation, the contrast between profile and non-profile is basically discrete and grammatically significant. In particular, the nature of its profile determines an expression's grammatical class.

For expressions that profile relationships we need to recognize a second type of prominence, pertaining to the relational participants, whose grammatical import is hardly less substantial. It is usual for one participant – which I call the **trajector** – to stand out as the primary *figure* within the profiled relation. Additionally, there is often a second "focal" participant – termed the **landmark** – with the status of secondary figure. Observe that two expressions, e.g. *before* and *after*, may invoke the same conceptual content and even profile the same relationship within it (in this case one of temporal precedence), yet differ semantically because they impose opposite trajector/landmark alignments. While participant prominence may in general be a matter of degree, I believe that trajector and landmark status represent distinct quantum levels, and that they furnish the ultimate basis for the notions **subject** and **object**.

A kind of quantization can also be observed in semantic change. Consider various uses of the preposition *across*:

(6) a. *The child hurried across the busy street.*
[profiled objective movement by trajector]
b. *The child is safely across the street.*
[static location resulting from unprofiled, past, actual movement of trajector]
c. *You need to mail a letter? There's a mailbox just across the street.*
[static location as goal of unprofiled, potential, future movement of addressee]
d. *A number of shops are conveniently located just across the street.*
[static location as goal of potential movement by a generic mover]
e. *Last night there was a fire across the street.*
[static location, no physical movement necessarily envisaged at all]

In (6a), *across* profiles objectively construed motion through space on the part of the clausal trajector (*the child*). In (6e), this sense of movement is reduced to subjective motion (i.e. mental scanning) along a comparable path on the part of the conceptualizer. The transition between these two meanings does not occur in a single jump, nor is it continuous. Rather, it involves discrete changes in a number of specific factors, producing intermediate cases like (6b–d). Among these factors are profiling (which shifts from the motion to the resultant location), the status of the motion (from actual to potential, from objective to purely subjective), as well as the identification of the mover (trajector, addressee, generic, conceptualizer). While the overall effect is to **subjectify** the conception of motion, this is the cumulative product of discrete steps along

several parameters. The example proves not to be atypical of semantic change (Langacker, 1999c).

Now that we have examined the "internal structure" of conceptions, including both content and construal, it is time to recall the working hypothesis advanced earlier: internally, discreteness predominates (a more cautious phrasing is that continuity is circumscribed and mitigated in various ways); by contrast, semantic effects due to "external" factors – i.e. relationships with other conceptual structures – are basically continuous. These external factors will now be briefly discussed. While they tend to be neglected, I do not regard them as incidental or even subsidiary, but as integral components of linguistic meaning. Moreover, they would seem to be essentially continuous (although the discovery of significant quantization would not at all surprise me).

An important aspect of linguistic semantics is our ability to construe one structure against the **background** provided by another. There are many kinds of background, including previous discourse, pertinent assumptions and expectations, and – in metaphor – the role of the **source domain** in conceiving and structuring the **target domain** (cf. Lakoff and Johnson, 1980, 1999; Lakoff and Turner, 1989; Turner, 1987). While it is not hard to think of possible quantization in this realm, I wish to emphasize an important parameter that may well be continuous: the *salience* of the background structure, i.e. its level of activation in the construal of the target. For example, once a discourse referent is introduced its salience tends to diminish through the subsequent discourse unless and until it is mentioned again. There are of course discretely different ways of doing so (e.g. with a pronoun, or with a definite article plus noun), reflecting quantized estimates of the referent's current status (cf. Givón, 1983; van Hoek, 1995, 1997). But its salience per se (and hence the effect of its background presence when it remains implicit) presumably varies continuously.

The relation between the source and target domains of a metaphor poses a number of thorny questions. To what extent do we understand the target domain prior to (or independently from) its structuring by the source domain? To what extent does target-domain reasoning depend on metaphorical structuring? To what extent do the source and target domains merge to form a "hybrid" or "blended" conception (Fong, 1988; Fauconnier, 1997; Fauconnier and Turner, 1998a)? Possibly we are dealing here with basically continuous parameters. Be that as it may, there are clearly many expressions that originate through metaphorical extension even though the target domain can easily be grasped independently. At least in such cases, we can speak of the gradual, presumably continuous "fading" of a metaphor, reflecting the declining likelihood and/or level of the source domain's activation on a given occasion of the expression's

use. Intuitively, for example, the literal sense of *fade* ('decrease in color intensity') is still reasonably salient in expressions like *fading metaphor*, *fade from memory*, etc. By comparison, *reflect* reflects more weakly the source domain of light and mirrors.

A related phenomenon is **analyzability**, the extent to which the component elements of a complex expression are recognized within it and perceived as contributing to its meaning. Thus *complainer* is more analyzable than *computer*, which in turn is more analyzable than *ruler* (i.e. 'instrument for measuring and drawing – "ruling" – straight lines'). We invariably interpret *complainer* as 'someone who complains', whereas we do not necessarily think of a *computer* specifically as 'something that computes', and a *ruler* is hardly ever thought of as 'something that rules [lines]'. I consider analyzability to be an important dimension of linguistic semantics. Indeed, I characterize an expression's meaning as comprising not just its composite semantic value, but also the entire **compositional path** which leads to it. In processing terms, analyzability is interpretable as the likelihood or degree to which component semantic values are activated along with the composite conception. Presently I have no linguistic evidence to suggest that this parameter is other than continuous.

Finally, I assume an "encyclopedic" view of linguistic semantics which denies the existence of any precise or rigid line of demarcation between knowledge that is "linguistic" and knowledge that is "extra-linguistic" (Haiman, 1980; Langacker, 1987, Ch. 4; cf. Wierzbicka, 1995). Our conception of a given type of entity – e.g. a *cat*, an *apple*, or a *table* – is almost always multifaceted, comprising a potentially open-ended set of specifications pertaining to any domain of knowledge in which it figures. Of course, these specifications vary greatly in their status. Some (like shape and primary function) are so "central" to an expression's meaning that they are virtually always activated when it is used. Other specifications (contingent knowledge, cultural associations) may be quite peripheral, being activated only in very special circumstances. A priori, it is reasonable to suppose that their likelihood and strength of activation vary continuously, being determined by such basically continuous factors as entrenchment, cognitive salience, and contextual priming.

The cases cited of continuous variation in how conceptions relate to one another all involve notions of cognitive salience and likelihood of activation. It is important not to confuse these matters of accessibility with the very different matter of how, in specific structural terms, the conceptions in question are linked together. We need to distinguish, for example, between the "vividness" of a metaphor on the one hand – i.e. how saliently the source domain is evoked in apprehending the target domain – and the metaphor's structure,

on the other hand. The latter comprises a particular set of mappings between source and target domain elements, resulting in a particular blended conception, regardless of how salient these structures are in relation to one another. More generally, cognitive semantics has demonstrated that **imaginative** capacities, such as metaphor, metonymy, fictivity, blending, and mental space construction, are pervasive and fundamental (e.g. Fauconnier, 1985, 1997; Fauconnier and Sweetser, 1996; Fauconnier and Turner, 1998a, 1998b; Kövecses and Radden, 1998; Lakoff and Johnson, 1980; Langacker, 1984, 1999b; Matsumoto, 1996a, 1996b; Talmy, 1996). Their imaginative nature does not entail a lack of structural specificity in how the constitutive structures are connected to one another. On the contrary, the key to understanding them is to elucidate these structural connections in precise detail.

As a final word, let me emphasize that discreteness vs. continuity may itself be a matter of degree, the various shades and types of discreteness being distributed along a (quantized) continuum. Depending on what we examine and what we wish to emphasize, both discreteness and continuity can be discerned in virtually any aspect of language and cognition. Our task is not to choose between them, but rather to explicate the specific ways in which this fundamental opposition plays itself out across the full range of linguistically relevant phenomena.

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CHAPTER 11

The iconic mapping of space and time in signed languages

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> [T]he world of images does not simply imprint itself upon a faithfully sensitive organ. Rather, in looking at an object, we reach out for it. With an invisible finger we move through the space around us, go out to the distant places where things are found, touch them, catch them, scan their surface, trace their borders, explore their texture. Perceiving shapes is an eminently active occupation. (Arnheim, 1974: 43)

1. Space, time, and language

Language both occurs in space and time and represents space and time. As a physical activity, language takes place in space and time at several different levels of organization. At the contextual level, the speaker is situated spatially and temporally when she speaks. The act of speaking involves the movement through space and time of articulators. Finally, the neural activity which underlies speaking also has a spatial and temporal dimension.

Language also represents space and time: we use language to talk about objects and events which exist in space and time. Even when we talk about concepts that have no referents in the physical world, we typically conceptualize these metaphorically as objects or events, as philosophers and linguists throughout the centuries have demonstrated (Lakoff, 1987; Lakoff & Johnson, 1980, 1999; Vico, 1774). In addition, as we will see in more detail later, it is even possible to consider two of the basic grammatical building blocks of language, nouns and verbs, to be highly abstract schemas of space and time.

The dimensions of space and time in which language is realized – contextual, articulatory, and neural – have differing roles within linguistic representation. At the contextual level, for example, space and time are an important aspect of language because they form the ground for the communicative

act. The speaker's location in space finds linguistic expression as a part of the ground ('here', 'there', 'behind' and so forth), as does the speaker's location in time ('now', 'tomorrow', and tense). The neural level, on the other hand, seems to play no role in grammar: the spatial and temporal dimension of linguistic processing in the brain is not reflected in grammar.

If we restrict our view only to spoken languages, it would seem that the fact that language takes place in space and time at the articulatory level plays little role in the grammar of languages. When we expand our range of data to include signed languages a different picture emerges. The fact that signed languages occur in space and in time takes on a potentially more interesting and important significance than it does for spoken languages. While the act of speaking takes place in space and time as the speech articulators move spatial locations in the vocal tract, the act of signing is uniquely different: unlike vocal tract articulators, which for the most part do their moving hidden from sight, the articulators of signed languages are visible.

Thus, while we have a situation that is strikingly similar on the one hand – articulators moving through time into different spatial locations – on the other hand we have a situation which is distinctly different: because the sign articulators are visible, language users can recruit the semiotic capacity of hands as objects moving in space to represent space and time. The articulators of signed languages are able to iconically represent the conceptual content of language.

In the next sections I will refine this initial description of the role of space and time in signed languages. To do so, I will adopt a linguistic framework which not only accounts for how space and time becomes the conceptual content of language, but which also grounds all of grammar within cognition.

I also will examine in detail how sign language articulators are conceptualized. In doing so, I will question a basic assumption regarding the nature of linguistic representation. Harris (1993: 12) notes that the most common view within the field of linguistics regards language as "a path running from sound to meaning." The Stoics were the first to formalize the two end points of the path, "signified" and "signifier." From the Stoics to Saussure this distinction, and the conception of their relation as two end points of a path, has been, again according to Harris, "an utterly fundamental insight, the first principle of linguistics" (p. 12).

I would like to call this fundamental assumption into question, at least for signed languages. I will suggest that the phonological manifestation, the signifier, of signed languages – hands moving in space and time – has conceptual import and thus is part of the signified. Stokoe (1991: 112) was the first to note this self-symbolic nature of signed languages; he called it **semantic phonology**:

> The usual way of conceiving of language seems to be linear: first there are the sounds (phonology), these are put together to make the words and their classes (morphology), the words in turn are found to be of various classes, and these are used to form phrase structures (grammar), and finally – the delay is built into this pedestrian way of thinking – the phrase structures after lexical replacement of their symbols yield meaning (semantics). A semantic phonology ties the last step to the first, making a seamless circuit of this pitty-pat progression. The metaphor for semantic phonology that jumps to mind is the Möbius strip: the input is the output – with a twist!"

We can think of this self-symbolic quality of signs as an example of recursion, because "recursive structures are built of components that are structurally identical to themselves" (Gelernter, 1998: 59). Stokoe saw this connection as well. He noted (1991: 112) that semantic phonology reflected a Gödelian self-reference:

> An *s-p noun-verb* unit represents a word of sign language, it is both an agent-verb construct and in the lexicon a formal noun or verb or other part of speech of the language, and it can combine in the normal way with others like it to make a grammatical noun-verb structure. This structure in turn has meaning (actually it always had).

Finally, I will suggest that the articulators of signed languages do not directly represent objects and events in the real world. Rather, conceptualizations of the articulators are mapped onto conceptualizations of the world; in some cases, conceptualizations of articulators are mapped onto conceptualizations which have no existence in the physical world, for example, grammatical categories. Since conceptualization is important for both sides of this symbolic equation, I will adopt the linguistic framework of cognitive grammar in order to understand how it is that signed languages iconically map space and time.

First, however, a bit of background on the nature and history of signed languages is in order, and it is to this that we now turn.

2. Signed languages

Signed languages are natural human languages used by deaf people throughout the world as their native or primary language (Wilcox & Wilcox, 1997). Although no formal survey of the world's signed languages has ever been conducted, the number of signed languages studied by linguists is well into the hundreds.

Signed languages are not invented languages. They are natural human languages which have arisen by the same diachronic processes which have led to the diversity of natural spoken languages. Although signed languages have been permitted in education of the deaf only in the last few centuries, and the scientific study of these languages is much younger still, there is no reason to suspect that natural signed languages are young languages.

Signed languages are not representations of spoken languages. They are independent languages with their own lexicons and grammars. Like spoken languages, signed languages may be classified into genetic or family groups. These genetic relations follow the historical development of signed languages, and so do not reflect the same relations as may exist for spoken languages. For example, American Sign Language (ASL) and Russian Sign Language are related to French Sign Language; ASL is unrelated to British Sign Language (BSL).

ASL, which will be the language most discussed in this chapter, is the primary language – in other words, the language used by members of the deaf community in face-to-face communication, learned either as the first language or a second, preferred language – of an estimated 100,000–500,000 Americans, including Deaf people, hearing children of ASL-using deaf adults, and adult deaf signers who have learned ASL as their second language.

3. Iconicity and signed languages

Two important historical and philosophical streams have had a profound impact on the scientific study of signed languages. The first is the widespread view that signed languages are not language but merely stylized gestures. This view had a powerful influence in deaf education and, as a result, on the lives of deaf people. It has only been within the past 50 years that linguists have demonstrated that signed languages are in fact true human languages.

The second stream was the influence that Cartesian philosophy had on the field of linguistics. I have suggested (Wilcox, 2000) that the Cartesian tradition in linguistics has resulted in three theoretical dualisms: mind versus body; language versus gesture; and language versus sign. The first, mind-body dualism, is the most important for our present discussion.

One way in which mind-body dualism has influenced our understanding of language is in the commonly accepted separation of form and meaning. The paradigm case for this bifurcation comes, not surprisingly, from Chomsky (1957:93):

> A great deal of effort has been expended in attempting to answer the question: "How can you construct a grammar with no appeal to meaning?" The question itself, however, is wrongly put, since the implication that obviously one can construct a grammar *with* appeal to meaning is totally unsupported. One might with equal justification ask: "How can you construct a grammar with no knowledge of the hair color of the speaker?"

The bifurcation of form and meaning is also present in the design feature of language called *duality of patterning*, which captures the well-documented fact that the meaningful parts of language (morphemes, words) are made up of meaningless parts (phonemes). It is duality of patterning which semantic phonology calls into question by suggesting that the signifiers of signed languages, (our conception of) the physically moving articulators, have conceptual import.

The specter of iconicity thus makes its appearance in Cartesian mind-body dualism: if true language depends upon the separation of form and meaning, then to the extent that a communication system is iconic, it is regarded as less of a true language. While spoken language linguists have begun to explore the role that iconicity plays in the linguistic structure of spoken languages (Givón, 1984, 1989; Haiman, 1985), much of the literature on iconicity in signed languages may be viewed as an attempt to constrain the linguistic significance of iconicity, to argue that while iconicity may be present it plays little if any role in the grammars of signed languages.

Within the sign linguistics literature, iconicity has typically been viewed as a relation between linguistic form and reality. Wilbur, for example, defines iconicity as "a reflection in language of the actual state of affairs in the real world" (Wilbur, 1987). Valli and Lucas (1995) regard the iconic relation to be one in which "the form of the symbol is an icon or picture of some aspect of the thing or activity being symbolized" – again implying that the relation is between linguistic form and some objective, uninterpreted world.

Frishberg (1975) argues that historical change acts to erode iconicity and heighten the arbitrary nature of ASL. She reports an extensive study of historical change in ASL in which signs change their phonetic shape, resulting in a loss of iconicity. Frishberg only examined lexical data, however, which left open the question of what role iconicity plays in grammar.

Klima and Bellugi (1979) expanded the scope of investigation to include grammatical, primarily morphological, data. They claimed that the grammars of signed languages act to "submerge" any inherent iconic properties of individual lexical signs (Klima & Bellugi, 1979: 30):

> Regular grammatical processes operate on ASL signs without regard to any iconic properties of the sign themselves; rather, they operate blindly on the form of signs. One of the most striking effects of regular morphological operations on signs is the distortion of form so that iconic aspects of the signs are overridden and submerged.

Their example is instructive. They describe the morphological change which marks intensification on certain statives in ASL. This regular change consists of a slight initial hold on the movement of a sign followed by a rapid movement. When applied to the ASL sign SLOW, the resulting sign means 'very slow'. Klima and Bellugi point out that the sign VERY-SLOW is made with a fast movement – faster than that used in the sign SLOW: "Thus the form of 'very slow' is incongruent with the meaning of the basic sign" (Klima & Bellugi, 1979: 30).

The form VERY-SLOW is multi-morphemic, consisting of the root form, the stative SLOW, and a bound, grammatical form expressing the intensifier translated here as 'very'. While the composite form does not iconically reflect the meaning of the lexical root (the form 'slow'), it does iconically represent the grammatical morpheme indicating intensity. Intensity can be understood metaphorically in terms of the build up and sudden release of pressure. A prototypical, real world example of intensification is a closed container that has been thrown into a fire. Heat from the fire causes pressure inside the container to build up, eventually causing the container suddenly and explosively to burst open.

In the ASL grammatical form meaning 'very' this build up of intensity is iconically signaled by a build up of muscular energy in the initial hold of the sign's movement. Then, this metaphoric pressure is released, resulting in a sharp, energetic movement. Thus, the grammar of ASL has not submerged iconicity; rather, iconicity has shifted from the lexical form to the grammatical marker of intensity.

Valli and Lucas (1995) also claim that while iconicity may be present in the lexicon, it plays no role in explaining grammatical processes in ASL. Discussing morphologically related noun-verb pairs in ASL, for example, they state (Valli & Lucas, 1995: 7):

> It is probably true that the form of the sign SIT is an iconic representation of human legs sitting ... [However,] focusing on its iconicity will not provide much insight into the interesting relationship between SIT and the noun CHAIR, and other noun-verb pairs.

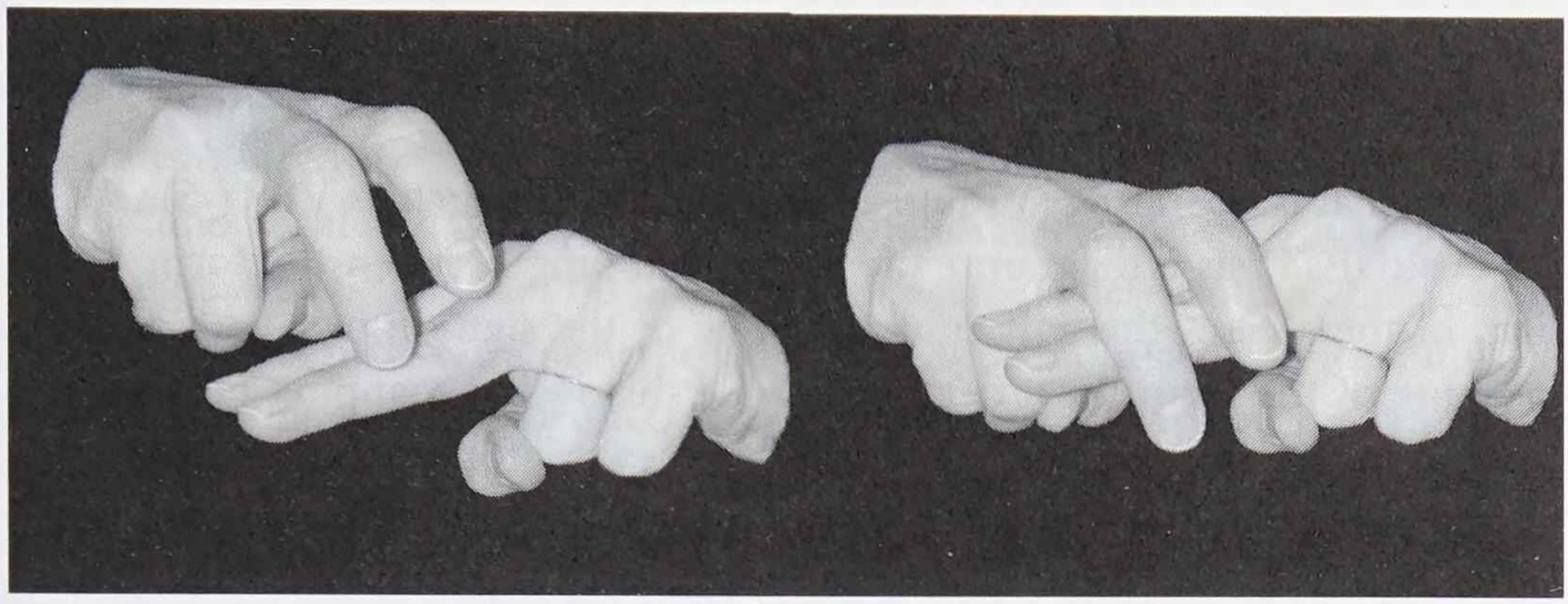


Figure 1. The ASL verb 'sit'.

Valli and Lucas are suggesting that while the shape of the hand may iconically represent human legs dangling off a chair (see Figure 1), the relation between morphologically related nouns and verbs, such as CHAIR and SIT, is not iconic. Similarly, Valli and Lucas (1995) claim that verbal morphology is not iconic: "Nor will [iconicity] help explain how the movement of SIT can be modified to mean SIT FOR A LONG TIME (slow, circular movement) or SIT ABRUPTLY (short, sharp movement)" (Valli & Lucas, 1995:7).

I will show below that both of these claims are incorrect. We can already see a problem for the argument against iconicity in the description that Valli and Lucas offer of the articulatory features of the aspectual morphology marking these two verb forms: is there really no relation between meaning and form when the durative form meaning 'for a long time' is represented by slow, circular movement, or in an inchoative form meaning 'a rapid change of state' (in this case, from standing to sitting) that is represented by a short, sharp movement?

As opposed to those who saw only a tension between language and iconicity, Stokoe (1986) recognized that the visible articulators of signed languages are semiotically rich, containing all three of the Peircean aspects of a sign: icon, index, and symbol. Stokoe noted that signs not only exhibit what Peirce termed image iconicity (that is, the iconicity reflected in the resemblance between the form of the sign SIT and human legs), but also a near-universal tendency to diagrammatic iconicity (Stokoe, 1986:179):

> If a hand (or both of them) plays a role in the sign's formation, it is quite possible, given the testimony of all of the world's signed languages so far studied, that the hand's configuration signifies the actor more than it signifies the

> action, and that the hand's action or movement signifies more the signified action than the actor.

Clearly what is operating in multi-morphemic forms such as VERY-SLOW or SIT-ABRUPTLY is a diagrammatic iconic mapping between the form of the sign, in these cases the particular dynamic of the sign's movement, and the meaning of the form. In order to examine this iconic mapping of time and space in more detail, we need a linguistic framework for describing the semantic and the articulator characteristics of a sign. It is to this framework that I now turn.

4. Conceptualizing the articulators

> We distinguish between things and happenings, immobility and mobility, time and timelessness, being and becoming. . . . Happenings are almost always activities of things. . . . Pure, unattached action is rare; but it exists. . . . When we distinguish the flight patterns of a distant swallow from that of an airplane, the object is reduced to a shapeless dot and we can be said to be seeing pure movement – an experience similar to that of hearing a musical sound move along the rises and falls of a melody. Mostly, we are in the presence of objects, which appear to us as stable entities, and actions performed by them. The gestures of a speaker are actions, but the speaker himself is perceived as a persistent thing, whatever biologists and physicists may say to the contrary. Even a cloud is experienced not as an event, but as an object in transformation; and the same is true for examples in which change does not depend on movement – a lobster turning red, a potato getting tender. (Arnheim, 1974: 372–373).

4.1 Language and symbolization

Cognitive grammar (Langacker, 1987, 1991a; Langacker, 1991b) posits that all elements of language – not just words but also elements smaller than words such as morphemes and elements larger than words such as grammatical constructions – are symbolic structures. They are symbolic structures because they consist of a correspondence between two simpler structures: a semantic structure and a phonological structure. On one side of the symbolic unit are semantic structures which embody meaning. On the other side are phonological structures which, at their most concrete level, are the physical expression of language, the signals which pass between participants in the communication act (see Figure 2a below, after Langacker, 1987: 80). For spoken languages these

signals are acoustic patterns, while for signed languages they are optical arrays. Whatever the form of the proximal signal, the distal source is articulatory gesturing produced by moving parts of the communicator's body – the tongue, glottis, and vocal folds for speaking, or the hands, face, and body for signing.

Linguistic notions also occupy semantic space. These notions range from fairly concrete, such as the way the word 'dog' is pronounced and its contextualized meaning, to fairly abstract, such as the way *verb* is pronounced and what it means – not a specific verb such as "throw" but the grammatical category *verb*. A critical claim of cognitive grammar is that *both semantic and phonological structures reside within the same semantic space*. Because of this, it is possible to compare the regions in semantic space occupied by the semantic and phonological poles of symbolic structures (see Langacker, 1987: 78–81, 91).

The typical case for language is that the semantic pole and the phonological pole of a symbolic structure reside in vastly different regions of semantic space. The sound of the spoken word "dog" has little in common with its meaning. This vast distance in semantic space, and the resulting incommensurability of the semantic pole and the phonological pole, is the basis for what linguists call the arbitrariness of the sign.

The semantic and phonological poles of linguistic symbols may, however, occupy regions of semantic space which are quite close. When such cases occur we talk of onomatopoeic expressions, or iconicity. For example, the famous expression of Julius Caesar, "Veni, vidi, vici," demonstrates how the semantic pole and phonological pole of an expression may occupy similar regions in semantic space: the temporal ordering of the events represented by the meaning of this expression is the same as the temporal ordering of lexical items at the phonological pole.

As a limiting case, the two poles of a linguistic symbol may occupy the same semantic space: they may be put into correspondence with each other and become self-symbolizing or self-referential. Langacker (1987: 91) explains:

> [W]hen the semantic pole of a linguistic symbol is itself situated in phonological space, comparison of the corresponding structures is feasible, and we recognize the expression as onomatopoeic when the structures show an appreciable degree of similarity. As a limiting case, moreover, a phonological structure can be put in correspondence with itself and hence be self-symbolizing.

Langacker offers the sentence "The boy went [NOISE]" as a spoken language example. Self-symbolization of this sort also appears in gesturing, for example when we say, "She looked at me and went [GESTURE]".

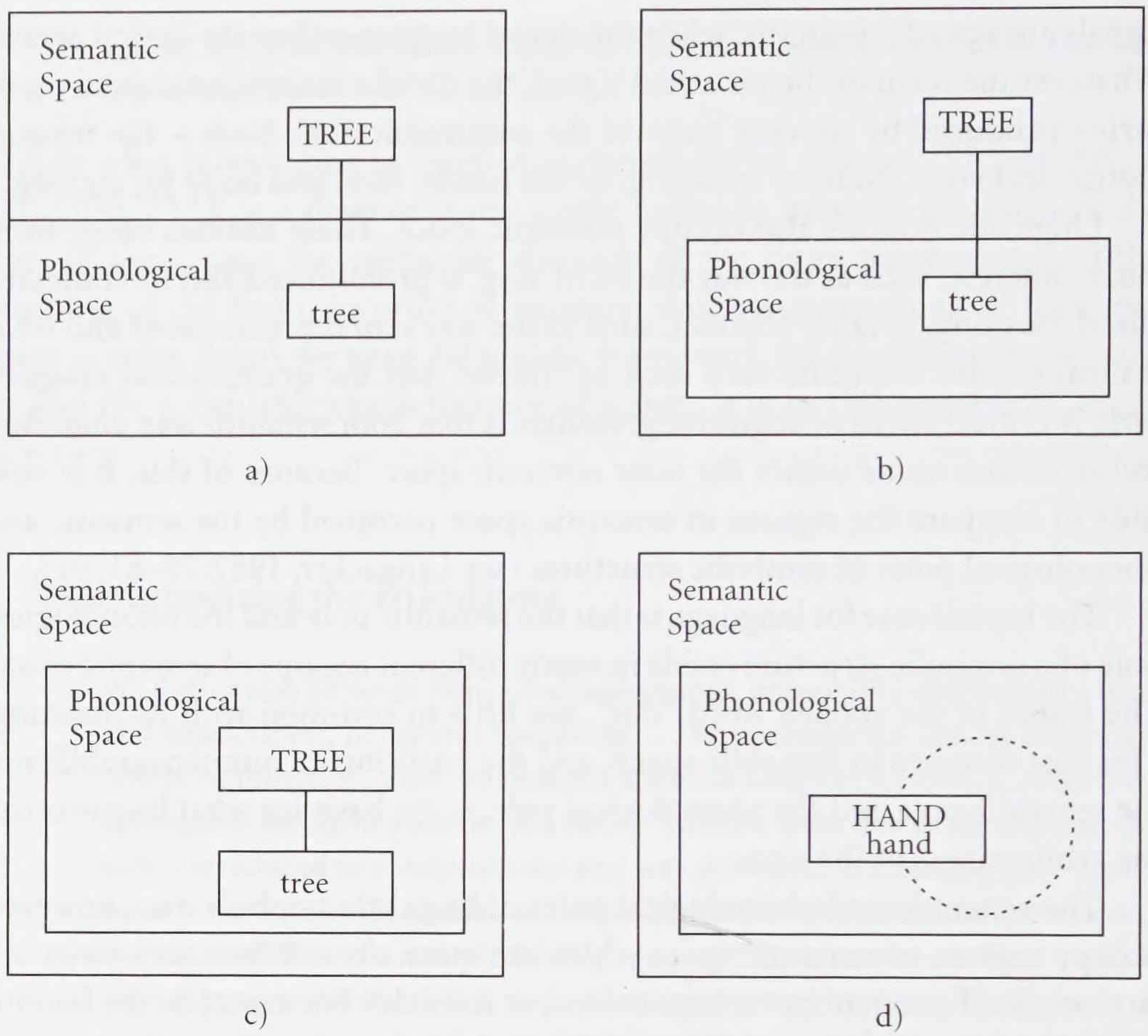


Figure 2.

We can see the same range of symbolization in operation in a signed language. While in a spoken languages such as English the conceptual distance between the phonological pole and the semantic pole of the lexical item *tree* is quite distant (Figure 2b), in ASL the sign is obviously iconically motivated: the sign *tree* resembles the general shape of a deciduous tree (Figure 2c). The limiting case of pure self-symbolization is approached when the signer's hand is used to represent a hand. For example, if a signer wished to state that a soccer player had received an injury to his hand, she would use her hand to represent the player's hand.

Thus, symbolization in language is not categorical; just as distances in space may vary continuously, distances in semantic or conceptual space between the semantic and phonological poles of symbolic units may also vary continuously. These examples demonstrate various points along this continuum. In addition, the example of self-symbolization is only an approximation

of the absolute limiting case. Observe that when a speaker says "And the boy went [NOISE]" the actual noise is not representing itself; rather, the speaker reproduces a new instance of [NOISE] and establishes a symbolic relation between the semantic and phonological poles. In the case of the signer using a hand to symbolize a hand, it is the signer's hand that is used, not the actual injured hand, which is (we hope) still attached to the injured player.

If the injury is to the signer's hand, as may be the case if the signer wished to tell someone where a cut had occurred on her hand when she was a child, then the absolute limiting case is much more closely approached. Still, though, this is not yet pure self-symbolization: it is not the signer's child-hand, the location of the cut may not be precisely the same, and so forth. The hand is still a symbol, a *representation* and not a *presentation*.

Thibault (Thibault, 1997: 279) makes essentially the same point concerning self-symbolization:

> This implies a continuum of possibilities. There may be maximal correspondence between the two poles, as in the limiting case proposed by Langacker, or minimal correspondence. Those showing 'minimal correspondence' are absolutely arbitrary in Saussure's sense. I would explain Langacker's limiting case in a slightly different way. Langacker's term 'self-symbolizing' suggests an identity relation between tokens such as /NOISE/, in his example, and the original referent situation which the token refers to. . . . Rather than 'self-symbolizing', I would say that examples such as these are in some ways analogous to direct speech, or quotation.

Thibault's point is well taken and points to the significance of this type of self-symbolization: it is the ontological beginning and possibly the evolutionary source of duality of patterning. As Haiman (1998: 150) notes: "Part of the driving mechanism which reduces words to meaningless sounds is erosion through repetition. In fact, *direct* quotation itself (essentially nothing more than the repetition of an utterance) does this kind of work through a single act." Haiman reinforces his argument by quoting Quine:

> From the standpoint of logical analysis, each whole quotation must be regarded as a single word or sign, whose parts count for no more than serifs or syllables. A quotation is not a description but a hieroglyph: it designates its object not by describing it in terms of other objects, but by picturing it. The meaning of the whole does not depend upon the meaning of the constituent words. (Quine, 1965: 26)

Haiman notes that Quine could easily have been describing duality of patterning (Haiman, 1998: 151). I would add that Quine could just as easily have been describing the use of a hand to represent a hand in a visible language.

4.2 Embodied conceptual models

Two basic conceptual models are required in order to describe the mapping of space and time in signed languages. These are the **billiard-ball model**, which describes the structure of events and will provide the framework for understanding grammatical constructs such as nouns and verbs; and the **stage model**, which systematically links our conceptual abilities to perceptual abilities.

The billiard ball model encapsulates our conception of the world as "being populated by discrete physical objects. These objects are capable of moving about through space and making contact with one another. Motion is driven by energy, which some objects draw from internal resources and others receive from the exterior. When motion results in forceful physical contact, energy is transmitted from the mover to the impacted object, which may thereby be set in motion to participate in further interactions" (Langacker, 1991b: 13).

The billiard ball model captures features of our conceptualization of space and time which appear in the grammatical categories of noun and verb. As Langacker notes (Langacker, 1991b: 14), the billiard ball model contains four elemental components: space, time, material substance, and energy. Consider the domain of instantiation for physical objects and for energetic interactions: physical objects, being composed of material substance, are instantiated in space; energetic interactions involve the transfer of energy and the resulting change, and are thus instantiated in time. Prototypical objects are spatially continuous and compact. This contrasts with their temporal expansiveness. When an object loses its spatial integrity, it ceases to be an object; however, objects remain objects over vast expanses of time. In fact, if an object did not remain stable over time it would not be perceived to be an object. On the other hand, interactions are spatially expansive yet temporally compact. An interaction consists of the objects which take part and their (possibly quite spatially expansive) locations, as well as their movement trajectories. Prototypical events are constrained in time: an interaction which takes place in a few seconds or less, such as two objects hitting each other, is more likely to be viewed as an event than an interaction which takes place over an expansive duration of time, such as continental drift.

A final characteristic which emerges from the billiard ball model is what Langacker calls *dependency relations* between objects and interactions. Objects

can be conceptualized independently of their interactions: we can conceive of billiard balls independently of their energetic interactions on a pool table. Interactions, on the other hand, do not exist entirely independently of their participants: "the conception of an interaction inherently presupposes some reference – however vague or schematic – to the entities through which it is manifested. Objects are therefore **conceptually autonomous**, and interactions **conceptually dependent**" (Langacker, 1991b: 14).

These two aspects of the billiard ball model – objects and their interactions – form the conceptual basis for the grammatical constructs of nouns and verbs within cognitive grammar. A noun is a region in some domain. Within the cognitive grammar framework, a region in some domain is given the technical term **thing**. Because our conception can become quite abstract, the domain need not be spatial. Nevertheless, prototypical nouns, like the objects in the billiard ball model, are spatially instantiated, compact, and temporally stable.

Langacker (1991b: 20–21) suggests that verbs comprise "a series of stative relations [a stative relation being a single, internally-consistent configuration] distributed continuously through conceived time, and further, that the conceptualizer scans the component states in a serial fashion (sequential scanning) rather than simply activating them holistically as a single gestalt (summary scanning)." This relation is said to comprise a **process**. Cognitive grammar thus claims that every noun profiles a **thing**, while every verb profiles a **process**.

The stage model captures certain aspects of our conceptual abilities by comparing them to the perceptual experience of a theater-goer watching the action taking place on a stage. Langacker (1991b: 284) explains:

> An observer's gaze is generally directed outward, toward other objects. At any one moment his field of vision subtends only a limited portion of his surroundings, within which his attention is focused on a particular region, just as a theater-goer focuses his attention on the stage. Now a stage is stable and inclusive, a fixed platform for the actors who move about and handle various props; in similar fashion, a viewer tends to organize the scene he observes into an inclusive **setting** populated by interacting **participants** who are small and mobile by comparison. There is further organization along the temporal axis, where clusters of contiguous interactions (particularly those involving the same participants) are perceived as forming discrete **events**. In summary, the stage model idealizes a fundamental aspect of our moment-to-moment experience: the observation of external events, each comprising the interactions of participants within a setting.

Thus, the stage model works in conjunction with the billiard ball model, which captures the nature of the moving participants which are being observed. The visual perception of these moving objects contributes to the experiential grounding of what Langacker (1991b: 285) calls **role archtypes**, upon which semantic roles are built:

> These archetypes reflect our experience as mobile and sentient creatures and as manipulators of physical objects. The archetypal agent is a person who volitionally initiates physical activity resulting, through physical contact, in the transfer of energy to an external object.

Together, the stage model, the billiard ball model, and role archetypes suggest that our *conceptual* abilities have a basis in our *perceptual*, primarily visual, abilities. Their appearance at the heart of grammar suggests that the joint visual perception and manipulation of physical objects interacting with other physical objects played a significant role in the evolution of language, a point to which I will return in Section 6.

5. Hands as objects of conceptualization

Cognitive grammar provides a framework for understanding how our conception of the world is grounded in our perception of the world. By grounding grammar in conceptualization, cognitive grammar provides a link between our perception of space and time as embodied in objects moving through continuous spatial and temporal dimensions, and the grammatical categories and constructions used to represent these same ideas. Cognitive grammar provides one more essential advantage in describing the representation of space and time in signed languages: it provides a framework for conceptualizing the articulators of signed languages. Since signed languages are produced by hands moving in space and time, we can rely on the same theoretical constructs to describe the hands as objects of conceptualization within a linguistic system.

In his pioneering analysis of the phonological structure of signed languages, Stokoe (Stokoe, 1960) identified three major parameters of sign language formation: handshape, movement, and location. Battison (1978) added a fourth parameter, orientation (the direction in which the palm faces). Since then, sign phonologists have offered a staggering array of phonological models of signed language, including segmental (Liddell & Johnson, 1989), syllabic (Wilbur, 1990), prosodic (Brentari, 1998), and visual phonology (Uyechi, 1996). In spite of the diversity of theories attempting to account for the forma-

tional structure of signed languages, certain spatial and temporal properties of signed language articulators are easily discerned:

1. The hands are autonomous objects manifest in the spatial domain.
2. Location and orientation are dependent properties of handshapes, also manifest in the spatial domain.
3. Movement is a dependent property of handshapes, manifest in the temporal domain.

Setting aside location for the moment, signs may be seen as prototypical instances of two major conceptual constructs of cognitive grammar: things (handshapes) and processes (movement). Hands are prototypical objects in interaction, either with other hands or other objects.

The location parameter spans both the spatial and temporal domains. Static phonological locations are spatial and exhibit certain unique features. First, they have no overt articulatory manifestation; it is only by being the locations for objects that locations become manifest. Second, these other objects need not have overt phonological realization. I will briefly explore the linguistic implications of these characteristics of location in Section 5.2.

Phonological locations may also be dynamic, involving a change in location. Change in phonological location may be used to represent a change in conceptual location; this change in location may either be literal (e.g. a person goes from Paris to Rome), or metaphoric (e.g. a change in possession). Change in location also includes the temporal domain: to move from position A to position B requires a change *over time*. Location is thus a complement to the movement parameter and may represent not a change in location, but movement through space or time. While movement through space and change of location may be objectively the same, the difference in construal has potential linguistic import. Movement through time need not involve movement through space. In Section 5.3, I will explore a few linguistic consequences of these aspects of location.

5.1 Hands as things, movement as process

One way in which handshapes represent things and movement represents process in signed languages is their role in classifier predicates. Classifier predicates are nearly universal in signed languages. Frishberg (Frishberg, 1975:715) first introduced the term "classifier" to describe a particular type of predicate in ASL in which a handshape is used to express a verb of motion:

ASL uses certain hand-shapes in particular orientations for certain semantic features of noun arguments. Thus the verb MEET has no 'neutral' form: the citation form actually means 'one person meets one person', or perhaps more specifically 'one self-moving object with a dominant vertical dimension meets one self-moving object with a dominant vertical dimension'. If trees started walking, they would MEET one another in the same way. Many of these classifiers are productive and analyzable, although not strictly transparent.

Classifiers are polymorphemic forms (Engberg-Pedersen, 1993) consisting of morphemes for movement, for manner of movement, for semantic characteristics of the moving object, for location in space, and so forth. Supalla (1978) suggests that the morphemes expressed by the sign's movement are roots, and the morphemes expressed by the handshape are affixes. According to Newport and Meier (1985: 885), the following formational patterns are found in these classifier predicates:

> The handshape is a classifier for the semantic category (e.g. human vs. animate nonhuman vs. vehicle) or size and shape of the moving object; the movement path (one of a small number of discretely different movements, e.g. straight vs. circular vs. arc) is a morpheme representing the path of motion of the moving object; the manner of movement is a morpheme for the manner of motion along the path (e.g. bounce vs. roll vs. random); a second handshape (typically produced on the left hand) is a classifier for a secondary object, with respect to which the primary object moves; and the placement of the second handshape along the path is a morpheme for the spatial relationship of the movement path with respect to this secondary object (e.g. from vs. to vs. past).

One fact is strikingly apparent in this description. First, across all of these forms what we find is that handshapes represent objects (and their features, and secondary hands represent secondary objects and their features, including their spatial relationship) and movements represent their actions (and their manner). Classifier predicates thus exhibit a complex but systematic pattern of iconic relations in which semantic objects (the **things** of cognitive grammar) are mapped onto handshapes, and process is mapped onto phonological movement.

5.2 Space and things

The cognitive grammar characterization of nouns as regions in some domain motivates the predominant representation of nouns by means of hands and their properties in signed languages. Hands as nouns are prototypical things in a number of dimensions: as physical entities they are regions in space, they

are composed of contiguous elements, and they are compact. However, things need not be composed of material substance.

The phonological parameter of location in signed languages is different from handshape along several dimensions. While locations are instantiated in the spatial domain, they fall on a continuum from being phonologically manifest (for example, the nose as a location in the ASL sign meaning "boring") to having no phonological manifestation. In the latter case, "virtual" locations or regions in space are used to represent various pronominal or noun-like entities.

One way in which locations as virtual things are used in signed languages is as replacements for nouns which are not present. The referents represented by these locations may be physical objects (people or other real-world objects) or abstract objects (such as textual or logical referents). The region in space is designated most often in signed languages by a pointing gesture; the handshape here then is not salient but merely a deictic indicator of the location, which is the intended "object". The handshape used to indicate the location varies across different signed languages. It also varies in systematic ways to indicate a possessive relation or an emphatic form. In ASL, for example, a location may be established representing a person pronominal. Pointing to the location with the extended index finger simply references the person ("he" or "she"). Pointing to the location with a flat, open hand, palm facing the location, marks a possessive ("his" or "hers"). Pointing to the location with a closed fist, thumb extended and upright (much like a "thumbs up" gesture) marks an emphatic: in answer to the question, "Who did it?" this ASL sign would mean, "He did it all by himself!"

These same processes are at work when the referent represented by the location is abstract. Abstract entities such as ideas, theories, claims, philosophies, and so forth may also be established in spatial locations in ASL discourse. By pointing to these locations, the signer references the abstract object previously established at that location. As for physical things, the handshape used to point to a location is merely an index to the location; the handshape here too signals whether the signer is referring to the referent associated with that location or is indicating a possessive relation.

Since spatial location and not handshape is the critical feature, we would expect that other means of indicating the location might be employed by signed languages; this is indeed the case. While it is most typical in ASL to use the hand to indicate a spatial entity, the location may also be indicated by eye gaze towards the intended location, a body shift in that direction, or even a slight movement of the head to orient it in the direction of the spatial location. It is important to note that these different methods of indicating a spatial lo-

cation, and thus of bringing into prominence the entity associated with that location, generate a complex array of grammatical constructions: it is not the case, for example, that orienting the body toward a location functions the same as indicating the location with an index finger point.

The variety of grammatical functions which rely on spatial location is much more detailed than has been discussed here (the reader is referred to Engberg Pedersen, 1993; Liddell, 1990 for more extensive discussion). What all these functions have in common, however, is that a region in space is used to represent a region in some conceived domain, and thus region in space can function as a nominal.

5.3 Space as time

Although space and time are distinctly different experiential phenomena, we nevertheless can and often do conceptualize time in spatial terms. Any number of languages recruit spatial directions and spatial terms for expressing temporal notions. In English, for example, we speak of time as an object ("the future is unknown"); a point in time may be construed as an object moving in space ("my 60th birthday is rapidly approaching"). It should not be surprising that signed languages also recruit spatial dimensions for the metaphorical expression of time.

Signed languages incorporate space as time in at least two ways: time may be conceptualized as an entity residing at a certain point in space, or the continuous flow of time may be conceived as movement through space. In the first case, ASL and several other signed languages (Engberg-Pedersen, 1993; Klima & Bellugi, 1979) often use various time-lines, setting spatial locations along a line to represent points in time. These time lines may be oriented in a front-to-back way, or in a side-to-side direction (see Figure 3). In the former (3a), which Engberg-Pedersen (1993: 80) calls the deictic time line, the future is typically indicated in front of the signer, the distant future even further away from the signer's forward direction, and the past behind the signer; the vertical plane of the signer's body represents current time. Although a point along the deictic time line is given a default meaning which is grounded to the moment of speaking, nondeictic values can be established in discourse.

Engberg-Pedersen (1993) calls the latter (3b) a sequence line; different times on the sequential time line, represented as spatial locations, are not deictically grounded to the time of speaking, but instead are relative to each other. Thus, "it is possible to establish reference points by representing time referents

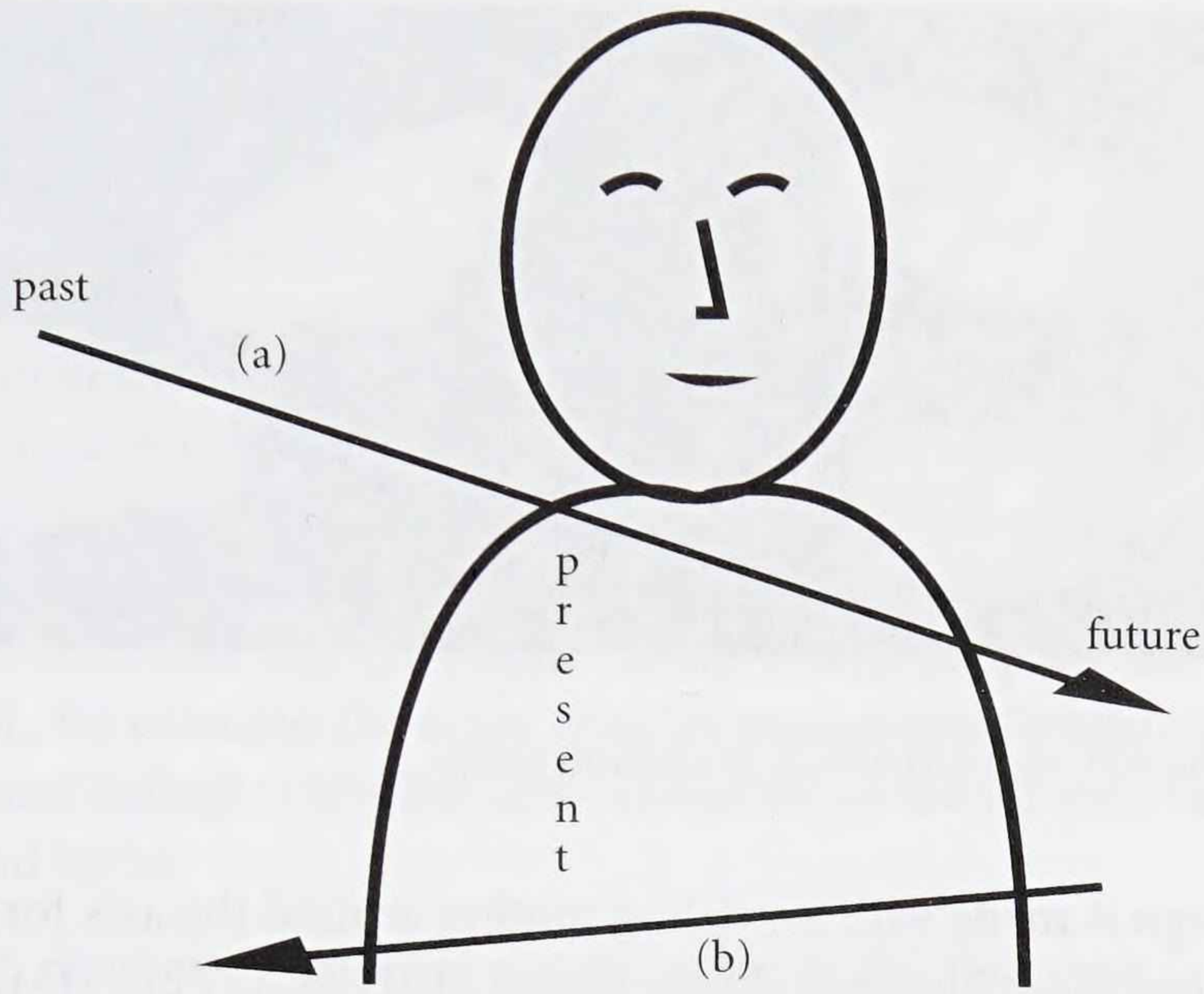


Figure 3. Time lines.

by loci of the line and talk about moments or periods before, after, or between reference points" (Engberg-Pedersen, 1993: 86).

When space is used to represent time in these time-line systems, a sign's movement does not indicate movement in time. For example, the ASL sign for 'tomorrow' moves in a forward direction, away from the signer, indicating a future point in time; the movement does not indicate movement through time until tomorrow.

It is possible however to map movement through time onto movement through space, for example by using the sequence time-line described above. In a conversation in ASL (*ASL across America: Detroit (Vol. 2)*, 1989), a deaf man is asked to describe the changes he has seen occur over the past several decades. He responds: MUCH CHANGE "A lot has changed." He then describes some of the things that have changed, and comments: CHANGE-OVER-TIME (restrictions on English grammar make it difficult to render an adequate translation of this complex verb form; the meaning is that slow and steady change has taken place during the time period being described).

The sign meaning 'change' in ASL is produced in citation form with two hands in identical handshapes, the index fingers of each hand bent and the tips touching the thumb (as in a pinching gesture), with the rest of the fingers curled into the palm. The hands contact (or come into close proximity with) each other at the point where the index fingers and thumbs touch the other

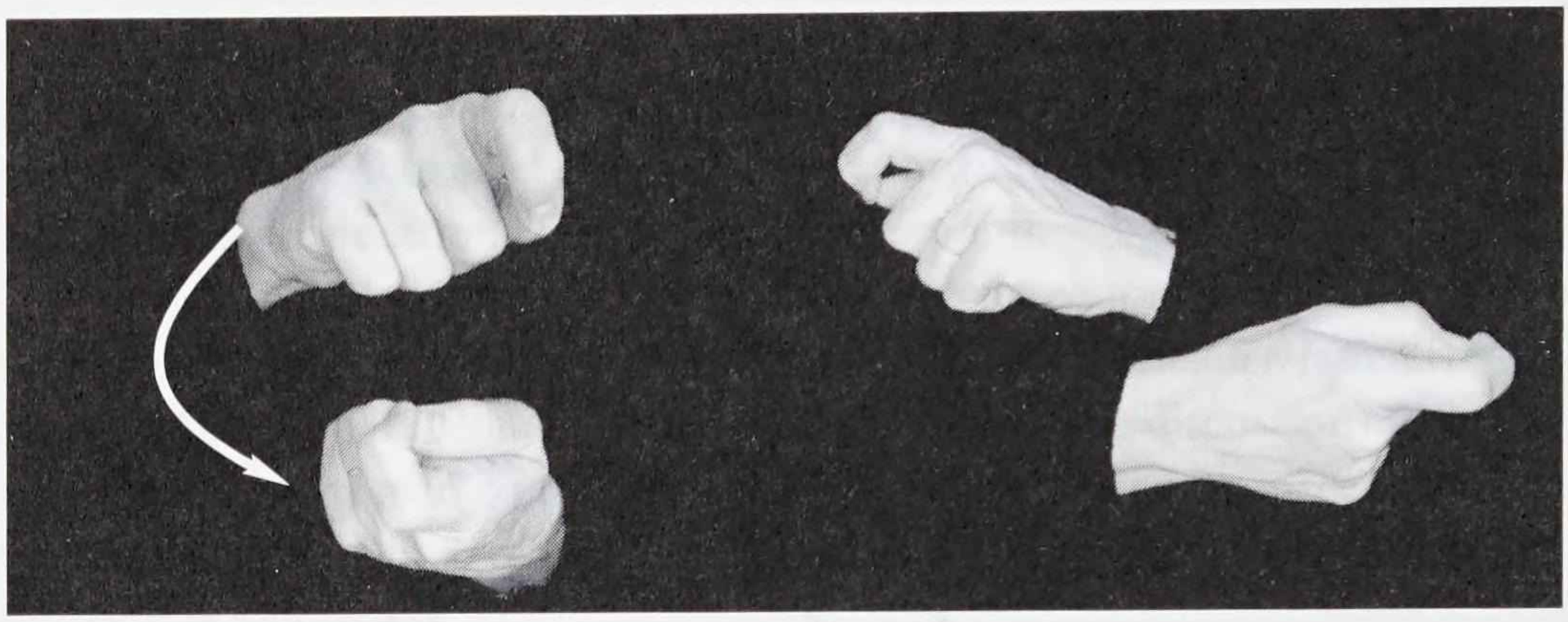


Figure 4. The ASL sign CHANGE in citation form.

hand; the sign is made with a twisting motion around the axis formed by this point of contact (see Figure 4). In the form CHANGE-OVER-TIME, the twisting motion of the sign is superimposed on a side-to-side movement along the sequential time-line. In this way, the form iconically maps movement through time onto movement through space.

An additional pattern of iconic mapping is revealed by comparing the two forms of CHANGE. The first form of CHANGE is a stative relation, or what Langacker terms a simple atemporal relation. As such, it lacks a positive temporal profile and relies on summary, as opposed to sequential, scanning. The atemporal relation views the scene holistically, designating only the final state of the overall process. This form of CHANGE is produced with only the sign's internal twisting motion. The hands move rapidly from their initial to final configuration; the final configuration is held slightly.

The second form, CHANGE-OVER-TIME, is a full verb form, or a process. This means that it is a relation having a positive temporal profile, and its evolution through time is portrayed by sequential scanning. Whereas the stative form CHANGE designates only the final state of a process, CHANGE-OVER-TIME designates a continuous series of states distributed over time. This form is produced with a slow, steady twisting motion (which, as described above, is spread across the slow, side-to-side movement along the sequential time-line).

As we saw for the use of space to represent things, the use of space to represent time is much more complex than presented in this brief description (see Engberg Pedersen, 1993). In all of this complexity, however, two iconic patterns of form and meaning emerge:

1. regions of space represent regions of time (time is conceptualized as a thing);

2. movement through space represents movement through time (time is conceptualized as a process).

5.4 Space and time, nouns and verbs

The full complexity of the iconic mapping of space and time in signed languages can be seen by examining the articulatory characteristics of nouns and verbs in ASL. In Section 3 we saw that many signed languages exhibit a systematic pattern between certain nouns and verbs in the language. Supalla and Newport (1978) described this systematic formal relationship in ASL noun-verb paris. In ASL, for example, the noun 'chair' is phonologically related to the verb 'sit'. Klima and Bellugi (1979: 295–296) elaborate on the formal characteristics of nouns and verbs:

> Both continuous and hold manner occur in the verb signs (a continuous sweep as opposed to a noticeable stop at the end of the movement); the related noun forms show a consistently restricted pattern: they are the same as the verb forms except that they have reduplicated movement and a restrained manner (that is, the muscles are tightened in performing the movement). As a result of the restrained manner the nouns are typically made with smaller movements than their related verbs.

I suggest that noun and verb forms in those signed language which have noun-verb morphology are iconic in two ways. First, as Valli and Lucas noted, both forms are often iconic of their lexical content: both 'chair' and 'sit' iconically represent legs. More importantly, these forms iconically represent their grammatical category: noun forms iconically represent nouns, and verb forms iconically represent verbs. Noun forms are articulated in a restricted region of space, making them conceptually things (in the technical cognitive grammar sense) at both their phonological and semantic poles. Verb forms make salient in articulation their movement through space, making them conceptually processes at both their phonological and semantic poles.

Further evidence of this iconic mapping of space and time in noun and verb forms comes from the systematic way in which the verb forms are grammatically marked to reflect verb aspect. Comrie (1976: 3) defines aspect as "different ways of viewing the internal temporal constituency of a situation." Aspect is different than tense: tense is deictic, relating time to the ground, while aspect refers to situation-internal temporal features such as the inception, duration, or completion of an event (Langacker, 1972).

Klima and Bellugi (1979: 292–294) describe a number of ways in which ASL verbs can be marked for temporal aspect (see Figure 5).

Two patterns are evident. First, aspectual marking on ASL verbs is iconic; changes in the temporal profile of the verb (the semantic pole) are represented by modifying the temporal profile of the sign's movement parameter. This need not be so; we could logically envision a signed language in which verb aspect is marked by changing the handshape parameter: the protracted form for 'look at' (Figure 5b) might be marked by producing the sign with a closed-fist handshape, the continuative form (Figure 5f) might be produced with an extended index finger handshape, and so on. In fact, no known signed language marks verb aspect in this way.

Second, the iconic mapping of time extends across the different aspectual forms. For example, Klima and Bellugi (1979: 292–294) give the meaning of the protractive form of 'look at' as "to stare at (uninterruptedly".) The semantic pole of this form thus appears to represent a situation in which there is no change to the internal structure, and no well-defined end-points, of the verb process. The stable situation of "looking at" persists unchanged through conceived time. This situation is described by Langacker (1991b: 21) as an imperfective process:

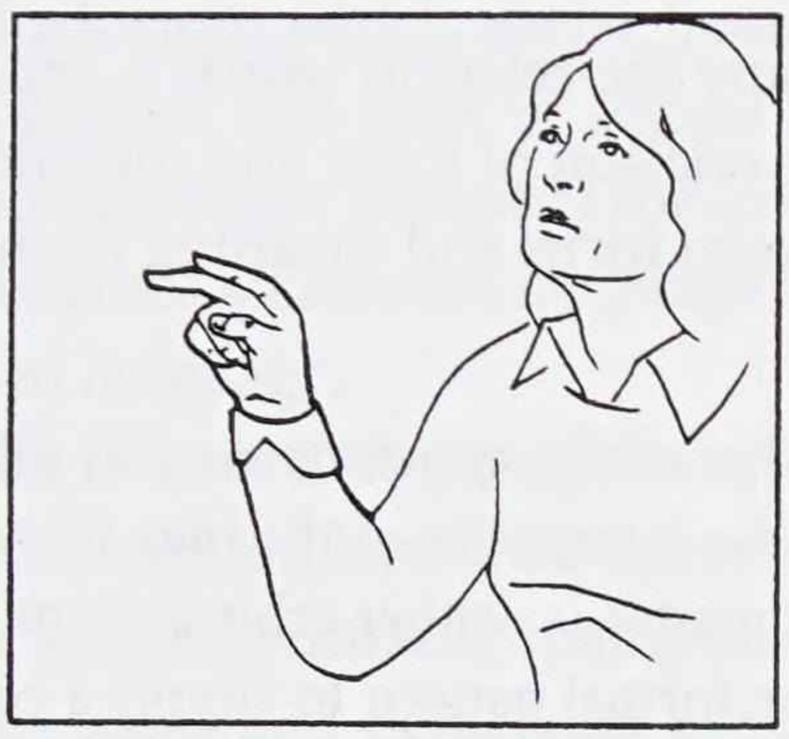
> In the simplest case, all the component states of a process are identical, i.e. the verb merely profiles the continuation through time of a stable situation. An example is *parallel* in its verbal use (e.g. *Line A parallels line B*). As a verb, *parallel* simply construes [a static situation] ... as extending through time (and scans sequentially through the component states).

Notice that the semantic structure of this verb in ASL is iconically represented by its phonological pole: the ASL verb form is articulated with a static form, unmoving and therefore unchanging. The characterization of the semantic pole as a continuation through time of a stable situation is represented at the phonological pole by the continuation through time of a stable situation.

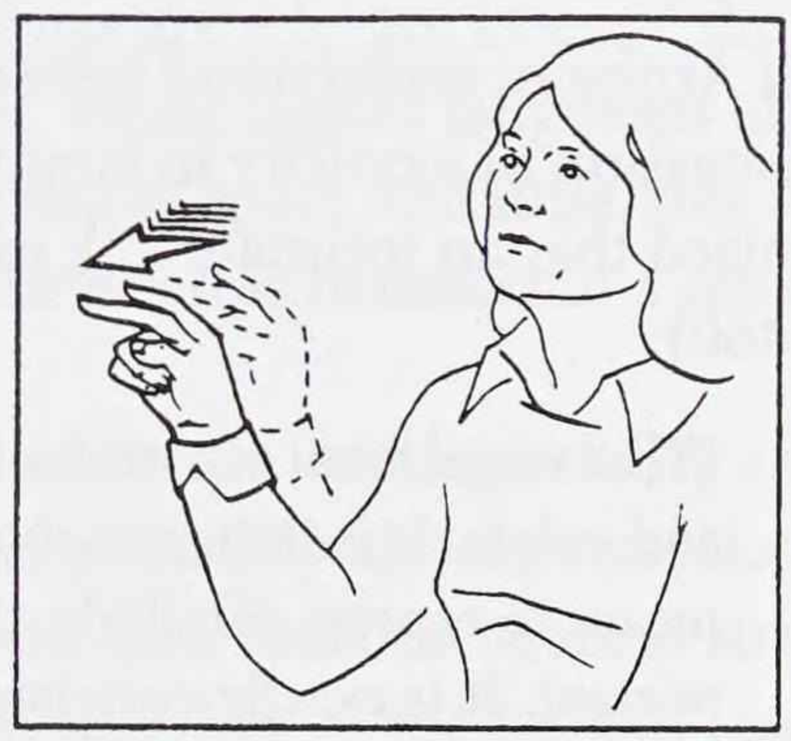
Klima and Bellugi (1979: 292) note these patterns as well, although they make no mention of the iconicity involved:

> The differences in meaning indicated by inflections for different grammatical categories are mirrored by general differences in form. The most salient formal characteristic of inflections for number and distributional aspect is *spatial* patterning, with displacement along lines, arcs, and circles in vertical and horizontal planes. By contrast, inflections for temporal aspect rely heavily on *temporal* patterning, making crucial use of dynamic qualities such as rate, tension, evenness, length, and manner in the movement of signs.

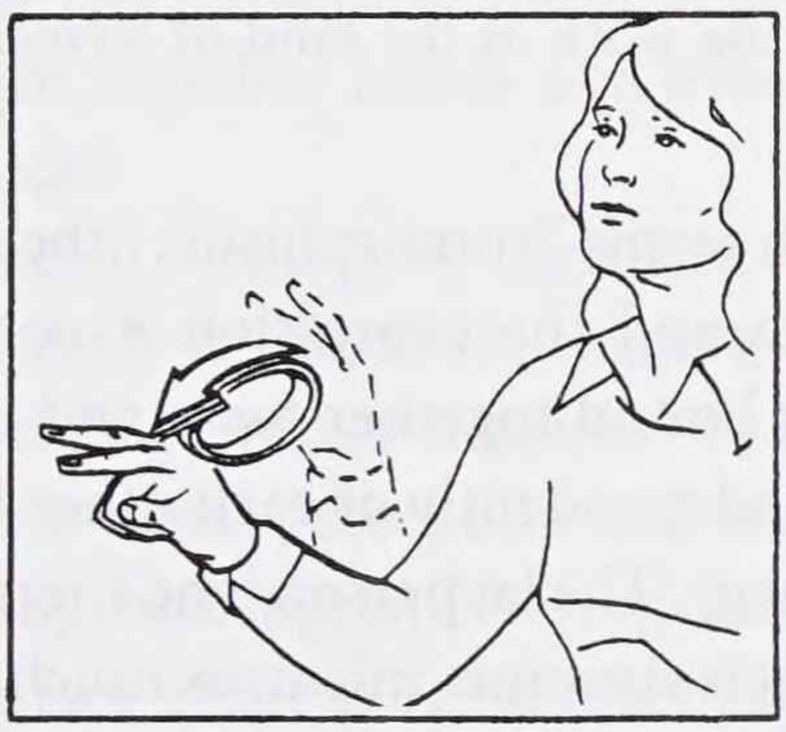
(a) LOOK-AT



(b) LOOK-AT[M:protractive]

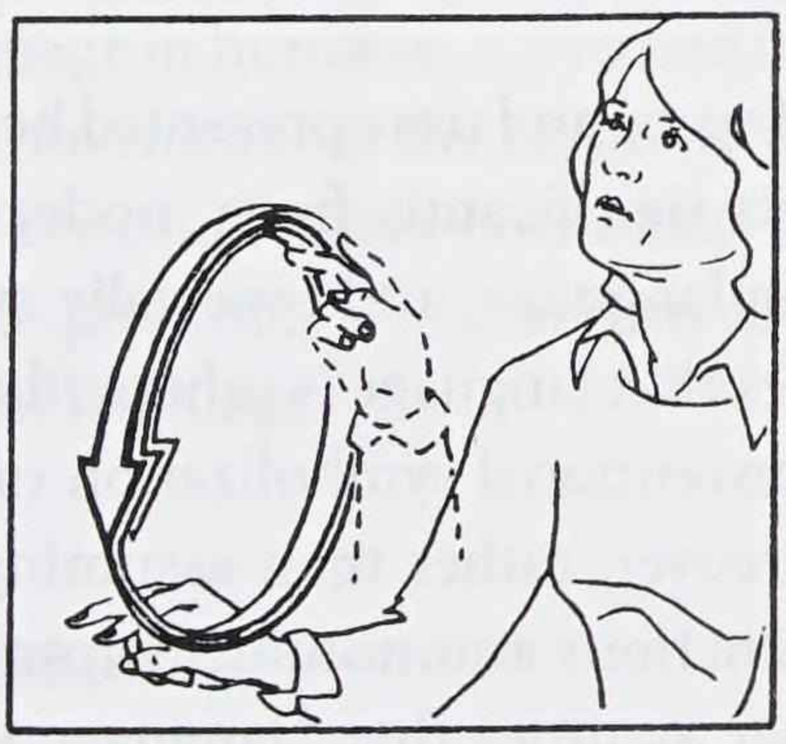


(c) LOOK-AT[M:incessant]



(d) LOOK-AT[M:durational]

(c) LOOK-AT[M:habitual]



(f) LOOK-AT[M:continuative]

(g) LOOK-AT[M:iterative]

Figure 5. Temporal aspect in ASL.

In this section I have offered data which demonstrates that, though often ignored and little understood, the iconic mapping of space and time plays an important role in signed languages. The questions that remains are why this should be so and what it tells us about the human language ability.

6. Grasping language

> If vision is an active grasp, what does it take hold of? (Arnheim, 1974: 43)

Rudolf Arnheim understood better than many the relation which is central to any discussion of iconicity in language – the relation of form and meaning. He recognized that an intimate link exists between form and meaning (Arnheim, 1974: 460):

> [T]he visual form of a work of art is neither arbitrary not a mere play of shapes and colors. It is indispensable as a precise interpreter of the idea the work is meant to express. Similarly, the subject matter is neither arbitrary nor unimportant. It is exactly correlated with the formal pattern to supply a concrete embodiment of an abstract theme. The kind of connoisseur who looks only for the pattern does as little justice to the work as the kind of layman who looks only for the subject matter.

What we have called iconicity here, Arnheim terms 'isomorphism': "the structural kinship between the stimulus pattern and the expression it conveys" (p. 450). For Arnheim, a dynamic dialectic bound together form and meaning – the two do not, indeed cannot, exist independently of each other in art. Neither do they exist independently in language. The layperson who merely listens for what sentences mean regardless of their structure misses as much as the linguistic connoisseur who regards language as pure structure, with meaning as unimportant as the speaker's hair color.

The description of the iconic mapping of space and time presented here has relied on a model of language which departs significantly from modern formalist linguistic theory. Rather than viewing language, and especially syntax, as pure structure, cognitive grammar assumes that language is inherently symbolic, "providing for the structuring and conventional symbolization of conceptual content" (Langacker, 1991a: 1). Moreover, rather than assuming that language is a self-contained system which functions autonomously from general cognitive processing, cognitive grammar assumes that "language is neither self-contained nor describable without essential reference to cognitive processing" (Langacker, 1991a: 1). Importantly, cognitive processes are held to

be of the type described by Varela and his colleagues (Varela, Thompson, & Rosch, 1991) as "embodied cognition". According to Mark Johnson (Johnson, 1987), embodied cognition may be characterized as image schemata: "An image schema is a recurring, dynamic pattern of perceptual interactions and motor programs that gives coherence and structure to our experience" (p. xiv). Human cognition is formed by these image schema, the fruit of our bodily experience with the world consisting of "human bodily movement, manipulation of objects, and perceptual interactions" (p. xix).

Thus, although the data offered here come from a rare group of languages, the conclusions which derive from this analysis are relevant beyond the mapping of space and time in signed languages. While signed languages afford a unique expressive potential for iconic mapping of space and time, this potential underlies all human language ability, whether it is manifest in a spoken or a signed language.

The factors that emerge as critical to the human language ability are embodied cognition based on active perception, primarily visual perception; and motor action, primarily manipulative actions. Like Stokoe's Möbius strip, the moving hand and perceiving eye are bound together in the human language ability. The remaining question is, what was it in our evolutionary history that brought together hands and eyes, motor action and visual perception, with language?

Recent research by Rizzolatti and his colleagues (Arbib & Rizzolatti, 1996; Rizzolatti & Arbib, 1998) suggests an answer. Rizzolatti reports on the function of so-called "mirror neurons" in Broca's area of primates and humans which mediate visual perception and recognition of manual motor actions such as grasping, holding, and tearing. Rizzolatti and Arbib (1998: 190) suggest that the "precursor of Broca's area was endowed before speech appearance with a mechanism for recognizing actions made by others." They conclude from this that "language in humans . . . evolved from a basic mechanism originally not related to communication: the capacity to recognize actions" (Rizzolatti, 1998: 193). If these conclusions are borne out, then the we may tentatively respond to Arnheim's question: "If vision is an active grasp, what does it take hold of?" It takes hold of language.

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John Benjamins Publishing Company

ISBN 90 272 5161 4 (Eur) / 1 58811 193 8 (US)