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The Role of Anxiety in Perceiving and Realizing Affordances

J. R. (Rob) Pijpers, Raoul R. D. Oudejans,
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Three experiments were conducted to examine the role of anxiety in perceiving and realizing affordances in wall climbing. Identical traverses were situated high and low on a climbing wall to manipulate anxiety. In Experiment 1, participants judged their maximal overhead reachability and performed maximal reaches on the climbing wall. Anxiety was found to reduce both perceived and actual maximal reaching height. In Experiment 2, participants climbed from right to left and back again on the high and low traverses, which now entailed an abundance of holds. Consistent with the reduction of perceived and actual maximal reaching height found in Experiment 1, anxiety led to the use of more holds. Finally, in Experiment 3, points of light were sequentially projected around the participants while they were climbing to measure attention. As participants detected fewer lights in the high-anxiety condition, it was concluded that anxiety narrowed attention. In general, the results underscored that the actor's emotional state plays an important role in perceiving and realizing affordances and that the perception of affordances changes as the accompanying action capabilities change.

When anxious, it is often difficult—quite literally—to keep things in perspective, as is illustrated by anecdotal evidence. In an attempt to conquer K2 (Karakorum Peak No. 2 in Pakistan; 8,616 m high), mountaineer Ronald Naar was faced with a small wall of ice. Usually, he would not have had any difficulty overcoming such an obstacle, but on this particular occasion—according to his own report—he suddenly froze with fear, and the ice wall seemed to him more problematical to surmount than the most horrifying key passages he had seen and conquered in his long

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career as a climber (Naar, 1996). Apparently, anxiety prevented Naar from detecting the relevant information and finding the correct solution to the motor problem confronted. Thus, anxiety may affect perception and, hence, the selection of actions.

The anxiety–performance relationship has been studied extensively and is one of the most widely investigated and debated areas in sport psychology (e.g., Woodman & Hardy, 2001).¹ A number of models have been put forward to describe and explain the relationship between anxiety and performance, such as the inverted-U hypothesis (e.g., Woodman & Hardy, 2001; Yerkes & Dodson, 1908), the drive theory of Hull and Spence (Hull, 1943; Spence & Spence, 1966), Apter's reversal theory (Apter, 1982; Kerr, 1997), Hanin's individualized zone of optimal functioning hypothesis (e.g., Hanin, 2000), the multidimensional models (Martens, Vealey, & Burton, 1990), and the cusp catastrophe model (Hardy, 1990, 1996). It is beyond the scope of this study to describe these models. Moreover, several excellent overviews of theories on anxiety and performance are available in the literature (e.g., Cox, 2002; Gould, Greenleaf, & Krane, 2002; Janelle, 2002; G. Jones, 1995; Landers & Boutcher, 1998; Raglin & Hanin, 2000; Weinberg, 1990; Woodman & Hardy, 2001).

Most important for now is that, despite the evolution of these models, the mechanisms underlying the relation between anxiety and performance are still poorly understood (e.g., Janelle, 2002; Mullen, Hardy, & Tattersall, 2005), as theorizing in anxiety research remains troubled by the absence of consistent experimental findings regarding the effect of anxiety on human motor performance (G. Jones, 1995; Kleine, 1990). One of the reasons for this state of affairs is probably the prevalence of product-oriented approaches in pertinent research that, by definition, ignore that the effect of anxiety on performance is mediated by a wide variety of processes (e.g., Collins, Jones, Fairweather, Doolan, & Priestley, 2001). To better understand this mediation, and thus to help disentangle the multifaceted relationship between anxiety and human motor performance, this study adopts a more process-oriented approach. Ecological psychology offers a conceptual framework for pursuing the latter kind of approach in the domain of interest, and as such provides, at least in our view, an expedient and promising theoretical framework for studying the influence of the actor's state variables, such as anxiety, fatigue, and anger, on perception and action, even though, admittedly, attempts in this direction have been few and far between.

In ecological psychology (J.J. Gibson, 1979/1986), perception is viewed as the active pickup of information specifying *affordances*, that is, the behavioral possibilities offered by the environment (also called *action possibilities* or *behavioral potential*; Bhalla & Proffitt, 1999; Proffitt, Bhalla, Gossweiler, & Midget, 1995). The theory

¹Anxiety is conceived as a multidimensional construct having a cognitive component (i.e., worry, apprehension) and a physiological arousal component (i.e., the physiological response to anxiety-inducing situations; Martens et al., 1990).

of affordances provides a conceptual framework for understanding the interactions between actors (humans and other animals) and their environment. It is founded on the premise that the environment is perceived in action-relevant terms, that is, in terms of what the actor can do with and in the environment. If the environment affords a particular action for a particular actor (human or animal), then that actor possesses certain properties that allow that particular action to take place in the environment. In ecological psychology, the latter properties are sometimes referred to as *effectivities* (Shaw, Turvey, & Mace, 1982; Turvey, 1992; Turvey & Shaw, 1979). In that account, affordances and effectivities are seen as complementary dispositional properties, both of which are necessary conditions for the actor–environment system to exhibit an action (Turvey, 1992).²

If an actor is perceiving affordances while engaged in a particular activity, he or she must be capable of perceiving the relation between environmental properties and the properties of his or her own action system. By implication, actions are “body-scaled” (e.g., Warren, 1984, 1988). For example, to successfully reach for objects, people must scale the distance of the object in terms of their effective reach actions, which are constrained by geometric measures (e.g., arm length, leg length; see, e.g., Carello, Groszofsky, Reichel, Solomon, & Turvey, 1989; Mark, 1987; Mark et al., 1997; Warren, 1984, 1988). Initial research on affordances was focused on these “invariable” intrinsic anthropometric body measures such as leg length (Warren, 1984), or arm length (Carello et al., 1989). Konczak, Meeuwssen, and Cress (1992) emphasized that action capabilities are not exclusively defined by anthropometrics, but that most perceptual–motor tasks are also subject to additional biomechanical constraints such as strength, limb mobility, and joint flexibility. They demonstrated that the perception of affordances (judgment of climbability of stairs) needs to be related to observers’ action capabilities, or, in Turvey’s (1992) terminology, effectivities (see also Cesari, Formenti, & Olivato, 2003; Choi & Mark, 2004; Oudejans, Michaels, Bakker, & Dolné, 1996; Oudejans, Michaels, Van Dort, & Frissen, 1996; Pepping & Li, 2000).

So far the role of the actor’s emotional state (i.e., anxiety or fatigue) in perceiving and realizing affordances has been addressed in only a few studies. Proffitt and Bhalla (Bhalla & Proffitt, 1999; Proffitt et al., 1995) conducted a series of experiments showing a relation between an actor’s state and the perceived steepness of hills. They found that as hills are harder to traverse when participants are ex-

²In ecological psychology there is an ongoing debate about the concepts of affordances and effectivities (e.g., Chemero, 2003; Heft, 2003; Michaels, 2003; Stoffregen, 2000, 2003). For instance, Stoffregen (2003) argued that affordances should be defined as emergent properties at the level of the animal–environment system rather than as properties of the environment that require complementary properties of the animal, that is, effectivities. In this respect Stoffregen’s definition of affordances differs qualitatively from that of Turvey (1992). However, irrespective of one’s position in this discussion, it is important to identify and understand how properties of the animal–environment system constitute opportunities for action, including the role of the actor’s emotional state in perceiving and realizing affordances.

hausted, wearing a heavy backpack, or older, the hills look steeper. It seems that the capacity to traverse a hill changes the perception of the steepness of the hill despite the fact that the actual steepness remains the same. Thus, there seems to be a functional adaptation of perception of action possibilities to the actual action capabilities.

Pijpers, Oudejans, and Bakker (2005b) confirmed such a relationship for overhead reachability, which they found to change as a function of exertion. On a climbing wall, participants repeatedly climbed series of trials resulting in increased levels of exertion. Before and during climbing participants judged their maximum reaching height, as well as perceived exertion. On a separate day, participants again climbed a number of trials while performing actual maximum reaches. Perceived maximal reaching height appeared to follow changes in action capabilities: When there were no changes in action capabilities—that is, no changes in actual maximal reaching height—no changes in perceived maximal reaching height occurred. Only when the actual maximal reaching height changed was this reflected in perceptual changes of maximal reaching height.

As far as we know, there is only one previous study that investigated the effects of anxiety on the perception of affordances. Bootsma, Bakker, Van Snippenberg, and Tdlohreg (1992) asked participants to judge whether balls that passed laterally at varying distances were reachable. They found that anxiety did not influence the average judgment of maximum reachable distance. However, Bootsma et al. did not examine whether anxiety had an effect on the actual maximum reaching distance. The selected affordance scaled with a physical characteristic (i.e., maximum reach, mainly determined by arm length), and was thus assumed not to be affected by the anxiety manipulation. However, as acknowledged by Bootsma et al., if an experimental manipulation directly affects the action capabilities of an observer, then a change in the perception of reachableness of approaching balls might be expected.

Thus, it seems that as long as participants' behavioral potential (i.e., actual action capabilities or effectivities) is not influenced by a state variable such as anxiety (or fatigue), one would expect that the perception of action possibilities is not influenced either. However, when a state variable does induce changes in a participant's behavioral potential, one would expect accompanying changes in the perception of the action possibility in question. The first goal of this study was to examine the role of anxiety in perceiving and realizing affordances. By using a climbing wall we determined perceived and actual maximal overhead reaching height under different anxiety conditions, which were created by placing the same climbing routes high and low on the wall (cf. Pijpers, Oudejans, & Bakker, 2005; Pijpers, Oudejans, Holsheimer, & Bakker, 2003). Overhead reaching and adequately perceiving overhead reachability are important to the performance of daily actions (e.g., grasping an item from the highest shelf in the supermarket), as well as in sports in which, for instance, a ball has to be caught or hit. Adequately perceiving overhead reachability is also essential in the task investigated in this study—

sport climbing—in which misperception may lead to falling. In Experiment 1, the effect of anxiety on perceived as well as actual maximal reaching height was investigated to determine whether changes in perceived maximal reaching height were accompanied by changes in actual maximal reaching height. In Experiment 2, we explored whether increased anxiety and the accompanying changes in perceived and actual maximal reaching height also affected participants' selection of action possibilities on the climbing wall. Finally, in Experiment 3, we investigated the impact of anxiety on attentional processes on the climbing wall.

EXPERIMENT 1

We expected that at higher levels of anxiety the actual maximal reaching height would decrease for two reasons. First, changing an individual's state (i.e., becoming more anxious) induces changes in movement execution such as higher muscle tension and jerkier, more rigid, and slower movements (e.g., Beuter & Duda, 1985; Collins et al., 2001; Mullen & Hardy, 2000; Pijpers et al., 2005; Weinberg, 1978). Second, reaching out as far as possible involves a chain of submovements such as stretching out the arm as far as possible; rotations in hips, back, and shoulders; stretching the legs; and standing on tiptoe; implying that any effect of anxiety on these submovements, however small, will result in a culmination of errors along an entire biokinematic chain, which enhances the possibilities for establishing anxiety effects on an outcome measure such as actual maximal reaching height (cf. Parfitt, Jones, & Hardy, 1990; Weinberg, 1990). In view of the theoretical considerations offered in the preceding, we further expected that the predicted decreases in actual maximal reaching height would be accompanied by decreases in perceived maximal height.

Method

Participants. A total of 12 female participants, mean age 23.0 years ($SD = 1.21$), volunteered to participate in the experiment. The participants, for the greater part university students, had no experience in climbing and were naive with regard to the purpose of the experiment. They all provided written informed consent.

The Dutch version of the A-Trait scale of the State-Trait Anxiety Inventory (STAI)³ was used as a standard check to measure trait anxiety (Spielberger, Gorsuch, & Lushene, 1970; Van der Ploeg, Defares, & Spielberger, 1979). The mean trait anxiety score for the participants was 30.8 ($SD = 6.28$), and was signifi-

³The STAI A-Trait scale is a self-report questionnaire that measures anxiety proneness—that is, the tendency to respond to situations perceived as thrilling with an elevation in state anxiety intensity. Scores range from a low of 20 to a high of 80 (Van der Ploeg et al., 1979, 1980).

cantly lower than the mean score for Dutch female college students ($M = 37.7$, $SD = 8.4$) obtained by Van der Ploeg, Defares, and Spielberger (1980) on a t test between a sample and a population mean (Thomas & Nelson, 1996), $t(11) = 3.83$, $p < .05$. The results indicated that the participants had no extraordinary tendency to respond to situations perceived as threatening with an elevation in state anxiety (e.g., Martens, 1982; Smith, Smoll, & Wiechman, 1998).

Experimental setup. Participants climbed on a vertical climbing wall (width = 3.5 m, height = 7.0 m; see Figure 1), which was set up in a large experimental room. The wall consisted of nine laminate panels with a gray grainy texture for friction. Holds could be bolted anywhere on the wall at relative distances of 0.24 m in a horizontal direction, and 0.17 m in a vertical direction. On the wall, two identical horizontal routes (so-called traverses designed by a professional route designer) were mounted (see Figure 1). Each traverse consisted of six footholds and six handholds of varying size and shape, which were all suitable for novice climbers. The mean height of Holds 3 and 4 (see Figure 1) of the low traverse (*low condition*) and high traverse (*high condition*) were 0.30 m and 3.60 m, respectively. (Participants stood on these holds when judging maximal reachability; see Procedure.)

One hold, the "assessment hold" (the black rectangle, see Figure 1), was movable in vertical direction. This hold was used to estimate the upper limit that participants perceived they were able to reach (the dependent variable perceived maximum reaching height), and that participants could actually reach (the dependent variable actual maximal reaching height). The assessment hold could be moved freely along a rail, which was placed between the laminate panels of the wall and extended the entire height of the climbing wall (see Figure 1). The assessment hold was connected with ropes that could be used to pull the hold up or down. Reference points were removed by covering a part of the climbing wall (0.40 m on both sides of the rail) with black tape. (Post hoc interviews indicated that none of the participants made use of reference points when making their assessments.) A flexible tape measure was used to measure the distance between the assessment hold and Hold 4 (see Figure 1) after each assessment, to determine perceived and actual maximal reaching height. Hold 4 was chosen because it provided a "natural" basis from which the investigated reaching action (perceived or actual) took place, especially because reaching was done with the left arm (see Procedure).

To enable participants to make assessments in the high condition, a large stepladder was used. The stepladder had a small platform that allowed participants to rest after having climbed it and to start the high traverse in the same physical (i.e., nonfatigued) condition as in the low traverse.

The participants wore well-fitting climbing shoes (Enduro 954, La Sportiva). In both conditions participants wore a climbing harness (Singing Rock). We used the so-called "top-roping" technique to ensure the safety of the participants. Top-roping involves "paired" climbing (Skinner & McMullen, 1993), that is, one end of the rope was tied onto the participant's harness, and the safety rope ran

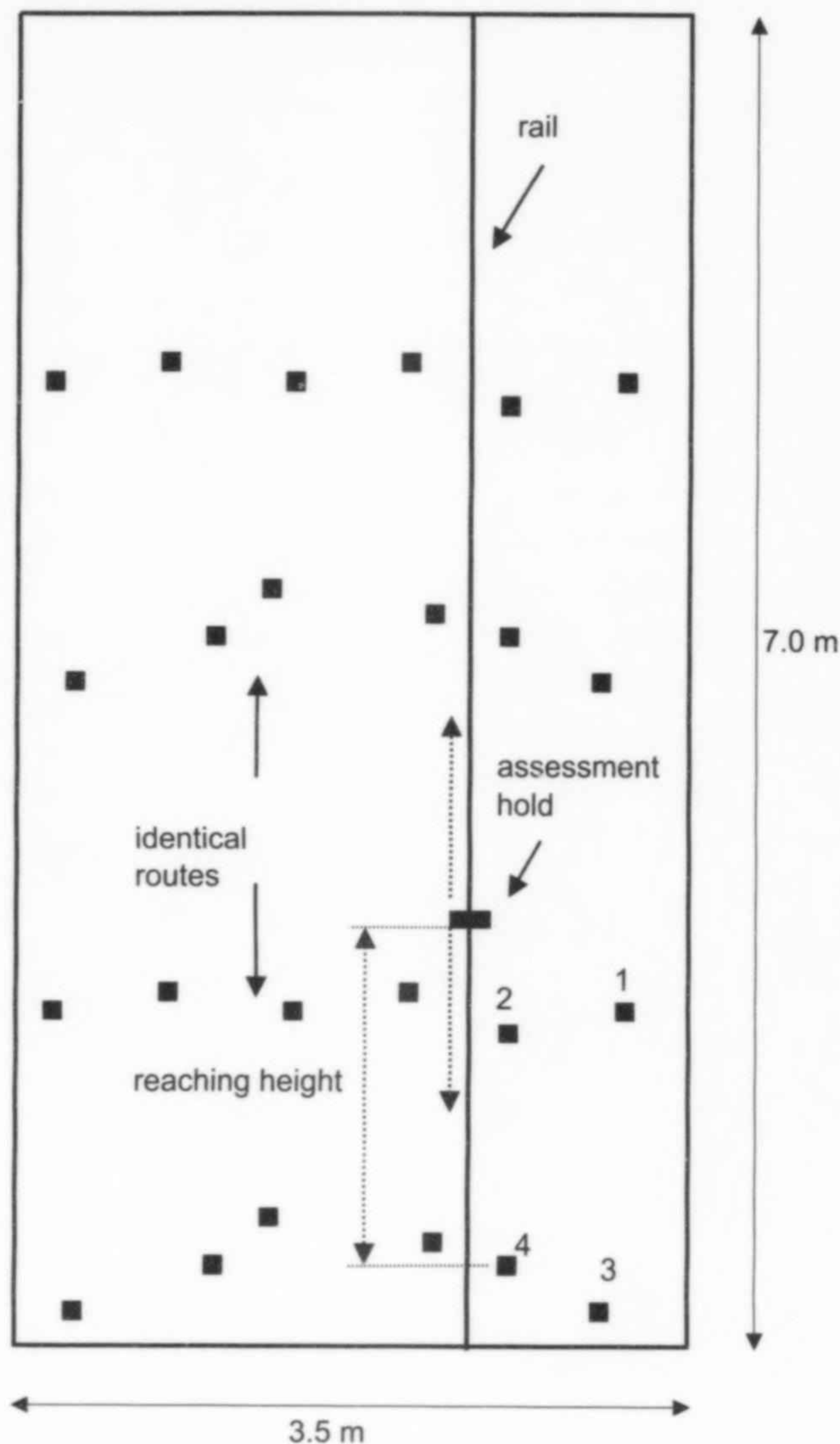


FIGURE 1 Front view of the layout of the climbing wall used in Experiment 1. Black squares indicate the positions of the holds. The routes in the low and high condition are identical. The assessment hold (indicated by the black rectangle) could be moved freely along the rail. Holds 1 through 4 indicate the position in which the perceptual judgments of maximum reaching height and actual maximum reaches were made (see also text).

up around a solid iron bar at the top of the climbing wall, and back to the ground. This end of the safety rope ran through the belay device on the belayer's harness. (The belayer is the person who manages the safety rope, preventing and protecting participants from falling if they lose their grip on the wall.) If properly applied, using the top-roping technique reduces the risk of a considerable fall to zero.

State anxiety was assessed by means of the "anxiety thermometer" validated by Houtman and Bakker (1989). The anxiety thermometer is a 10-cm continuous scale on which participants were asked to rate their anxiety feelings at a particular moment in time, ranging from 0 (*not anxious at all*) to 10 (*extremely anxious*). Participants had to place a cross on the 10-cm scale to indicate how they felt at a particular moment. The distance between the left end and cross (in mm) was used as a measure of the reported anxiety. Consequently, the anxiety thermometer provided a quick method for measuring state anxiety in contrast to the often-used Competitive State Anxiety Inventory-2 (Martens et al., 1990; for a critical discussion of the Competitive State Anxiety Inventory-2, see M. V. Jones & Uphill, 2004, and Woodman & Hardy, 2001), which would be unsuitable for our purposes (see also Pijpers et al., 2003). The validity and reproducibility of the anxiety thermometer are fair, with correlation coefficients ranging between .60 and .78. Based on these data, the anxiety thermometer is deemed an appropriate instrument for measuring anxiety in a threatening real-life situation (Houtman & Bakker, 1989). For each measurement, a separate anxiety thermometer was used.

During the assessments of perceived maximal reaching height, we recorded heart rate values every 5 sec using a Sporttester (Polar Electro-3000). Afterward, mean heart rate was calculated per condition. All assessments were videotaped using an S-VHS camcorder (sampling rate 50 Hz), allowing us to check specific aspects of the experiment if such a need arose.

Procedure. Participants were tested individually on a single day. Their total involvement in the experiment was approximately 1 hr. Participants were informed about the procedure of the experiment, and then asked to read and sign an informed consent statement. They completed the Dutch version of the STAI A-Trait scale (Van der Ploeg et al., 1979) and filled out an anxiety thermometer to familiarize themselves with this measuring device.

Participants were then briefed in detail about what was meant by *maximal reaching*, on which they had to base their estimates of maximal reaching height. For the purposes of this study, the maximal reaching height was defined according to the following reaching action (for the numbering of the holds low on the wall, see Figure 1): Each participant placed her left foot on Hold 4, right foot on Hold 3, right hand on Hold 1, and left hand on Hold 2, and then imagined that she would stretch upward as far as possible (keeping both feet on the holds; standing on tiptoe was allowed) using the left hand to grasp the assessment hold in such a way that it would be possible to hang onto it and to use it for climbing. Participants were not allowed to actually execute the reaching action.

Each participant was fitted with climbing shoes and harness, as well as a Sporttester. Prior to making the assessment of the perceived maximal reaching height participants were given the opportunity to practice on the wall, as brief hands-on experience with the task may yield perceptual information about climb-

ing actions having a substantial impact on participants' estimations of maximal reaching height (Pijpers et al., in press).

Subsequently, participants were asked to take position on the wall. The assessment hold (see Figure 1) was either lowered from about 1.5 m above Hold 2 (descending assessment) or pulled up from about 1.5 m below Hold 2 (ascending assessment), during which the participants had to verbally indicate when the assessment hold would just be reachable in the prescribed manner. Participants could fine-tune their judgments by telling the experimenter to move the assessment hold either up or down until they were confident that the assessment hold was at the perceived maximal reaching height. Then, by means of the tape measure, the distance was determined to the nearest millimeter; for accuracy reasons we always read off the tape measure at eye level. The descending and ascending assessments were presented in alternating order. One trial consisted of one descending and one ascending assessment. Consistent with previous research on perceptual judgment tasks using the method of limits (e.g., Mark, 1987; Mark, Balliett, Craver, Douglas, & Fox, 1990; Pufall & Dunbar, 1992), the average of the three descending/ascending combinations (i.e., three trials) was used as measure of perceived maximal reaching height for a given condition. Participants received no feedback about the accuracy of their assessments.

Perceptual judgments were made in a similar way high and low on the wall (high and low conditions were counterbalanced). In each condition participants performed three descending and three ascending trials. Immediately after each condition participants were asked to rate their feelings of anxiety by means of the anxiety thermometer. Participants were asked to recall how anxious they had felt during the assessments and to record this on the anxiety thermometer scale. This was used as the anxiety score for the condition in question.⁴

Participants were allowed a recuperation period of about 10 min after each condition. After the two perceptual judgment conditions, participants' actual maximal reaching height was determined: In both "actual" conditions, the participant stood on the footholds (right foot on Hold 3, left foot on Hold 4), grasped Hold 1 with her right hand (see Figure 1), and stretched out as high as possible with her left hand while the experimenter positioned the assessment hold in such a way that hanging onto it was just possible. The height of the assessment hold was measured. This procedure was repeated once; just as with the perceptual judgments, the mean of

⁴In retrospect, it might have been better if we had also asked participants to rate their feelings of anxiety briefly after performing the maximal reaches. However, as perceptual assessments and actual reaches were executed within the brief time span of about 25 min, we had (and still have) no reason to believe that participants' anxiety would have been different during the actual reaches in comparison to the perceptual assessments. Moreover, we found significant differences in anxiety between the high and low conditions on this climbing wall in all the climbing experiments that we performed (e.g., Pijpers et al., 2003, 2005). Even if participants had to climb high on the wall twice in the same experiment, anxiety was still significantly higher than in the low condition during the second time high on the wall (Pijpers et al., 2005).

the (two) assessments was the participants' maximal reaching height for the condition in question.

One of the experimenters served as belayer. In the low condition, the belayer acted so as to ensure that both conditions were similar for the climber. Each participant was informed before starting the climb in the low condition (mean height of the footholds, 0.4 m) that, despite the belayer, if she slipped she should break her fall herself, as the safety procedure would not be effective at that climbing height.

Statistical analysis. The effect of height (low-anxiety condition, high-anxiety condition) was tested using one-tailed paired *t* tests. Effect sizes (ES), indicating how many standard deviations the means under consideration differed, were calculated by taking the ratio of the difference between the two means and the mean within-cell standard deviation of the means (Mullineaux, Bartlett, & Bennett, 2001; Thomas & Nelson, 1996). Effect sizes of 0.2 or less, about 0.5, and 0.8 or more represent small, moderate, and large differences, respectively (Cohen, 1988). When necessary, two-factor repeated measures analyses of variance (ANOVAs) were used. Maughly's test of sphericity was used to determine whether there were any violations to sphericity for the repeated measures. If violations occurred, they were corrected according to the Huynh-Feldt procedure before determining whether the differences of interest were significant (Kinnear & Gray, 2000). Eta squared (η^2) assessed the explained variance in the ANOVA models. Pair-wise comparisons using *t* tests were made using the Bonferroni correction procedure (Kinnear & Gray, 2000) to identify specific mean differences when a significant main effect was found. The *p* values that are reported on the basis of this Bonferroni method are scaled to the .05 alpha level so that, as usual, *p* values smaller than .05 indicate a significant effect.

Results

State anxiety and heart rate. To determine whether the anxiety manipulation was successful, we performed a paired *t* test on both the anxiety thermometer data and the heart rate data. Participants reported significantly higher anxiety scores in the high condition ($M = 4.5$, $SD = 2.52$) than in the low condition ($M = 1.7$, $SD = 1.57$), $t(11) = 3.96$, $p = .001$, $ES = 1.35$. In addition, the mean heart rate (beats per minute or bpm) was significantly higher in the high condition ($M = 119.1$ bpm, $SD = 16.62$) than in the low condition ($M = 108.9$ bpm, $SD = 16.97$), $t(11) = 2.87$, $p = .008$, $ES = 0.61$. Thus, according to both measures, the manipulation of anxiety was successful—that is, in the high condition, participants were more anxious than in the low condition, implying that the high and low conditions indeed represented high-anxiety and a low-anxiety conditions, respectively.

Actual maximal reaching height. The average actual maximal reaching height was lower in the high condition than in the low condition (see Table 1). This

TABLE 1
Actual Maximal Reaching Height^a and Perceived Maximal Reaching
Height^a for the Conditions in Experiment 1

Variable	Condition			
	Low-Anxiety		High-Anxiety	
	M	SD	M	SD
Actual maximal reaching height	209.4	11.43	207.1	10.48
Perceived maximal reaching height	207.6	11.36	204.0	11.34
Trial 1	207.8	11.35	204.6	10.13
Trial 2	207.6	12.13	204.1	11.00
Trial 3	207.5	11.34	203.2	10.98

^aIn cm.

difference was marginally significant, $t(11) = 1.77, p = .052, ES = 0.20$, indicating that higher levels of anxiety seemed to have affected participants' actual maximal reaching.

Perceived maximal reaching height. A 2 (Height: low-anxiety condition, high-anxiety condition) $\times$ 3 (Trial: Trial 1–3) repeated measures ANOVA on the perceived maximal reaching height data (see Table 1) revealed a significant main effect of height, $F(1, 11) = 8.73, p = .013, \eta^2 = 0.44, ES = 0.34$, indicating that the average perceived maximal reaching height was significantly lower in the high-anxiety condition than in the low-anxiety condition. The main effect of trial and the interaction between height and trial were not statistically significant ($F_s < 1$).

Discussion

Self-reported scores indicated that participants felt more anxious in the high condition (anxiety thermometer score: 4.5) than in the low condition (anxiety thermometer score: 1.7). A score of 4.5 on a 10-point scale might be taken to imply that the anxiety was relatively low. However, a score of 4.5 indicates that participants felt more anxious than students who are about to enter a written examination (Houtman & Bakker, 1989), about as anxious as novice teachers just before a lecture (Houtman, 1990), and less anxious than youth speed skaters prior to the start of a 1500 m race at a national championship (Bakker, Vanden Auweele, & Moormann, 1992). In addition to the subjective experience, heart rate appeared to be significantly higher when participants were high on the climbing wall than when they were low on the climbing wall. Thus, despite the fact that we selected a low trait anxious sample of women, the results clearly indicated that the anxiety manipulation was successful.

The results showed that in the high-anxiety condition, participants' actual maximal reaching height was lower than in the low-anxiety condition, although the difference just failed to reach the 5% significance level. The decrease in actual maximal reaching height was accompanied by a decrease in perceived maximal reaching height. This finding is consistent with the theoretical expectation that the perception of affordances changes only as the accompanying action capabilities change (Bootsma et al., 1992; J.J. Gibson, 1979/1986). The decrease in actual maximal reaching height is also in keeping with anxiety-induced changes in movement execution, such as more muscle tension and jerkier and slower movements (Pijpers et al., 2003, 2005; Weinberg, 1978; Weinberg & Hunt, 1976).

Note that the absolute difference between the low-anxiety condition and the high-anxiety condition was (only) 2.3 cm for the actual maximal reaching height and 3.6 cm for the perceived maximal reaching height. However, in both cases, the range over which changes are to be expected is small. As for actual maximal reaching height, the values are comparable to loss in stature due to spinal shrinkage. Values of spinal shrinkage due to circadian variations as well as spinal compression that are reported in the literature vary from a few mm up to over 1 cm or up to 1% (see Van Dieën & Toussaint, 1993), implying a reduction of about 1.7 to 1.8 cm for 1.7 m tall persons, the mean height of our participants ($SD = 0.04$). In light of these numbers, an average momentary reduction of actual maximal reaching height of 2.3 cm due to anxiety can be considered substantial. Regarding perceived maximal reaching height, as participants' height was on average 1.7 m, it is highly unlikely that participants judged their maximal reach lower than 1.7 m. The range over which the judgments were made was maximally 40 cm, and probably even less. As such, the observed difference of 3.6 cm may also be viewed as substantial.

The question remains whether the anxiety-induced changes in perceived and actual maximal reaching height also lead to changes in the realization of action possibilities. For example, if one perceives a particular hold on the climbing wall as just reachable in a neutral condition but as no longer reachable when anxious, does that also lead to the selection of a hold that is safely within reach if such a hold is available? In Experiment 2, we addressed this question by examining whether anxiety and accompanying changes in perceived and actual maximal reaching height also affected participants' selection of action possibilities on the climbing wall, and, consequently, movement behavior.

EXPERIMENT 2

We asked participants to climb a horizontal traverse in two anxiety conditions, low (low-anxiety condition) and high (high-anxiety condition) on the climbing wall. To ensure that participants had the opportunity to select more holds than strictly necessary to climb the traverse, an abundance of holds (30) was used in building the traverse (see Figure 2). Previous studies (Pijpers et al., 2003, 2005) had demon-

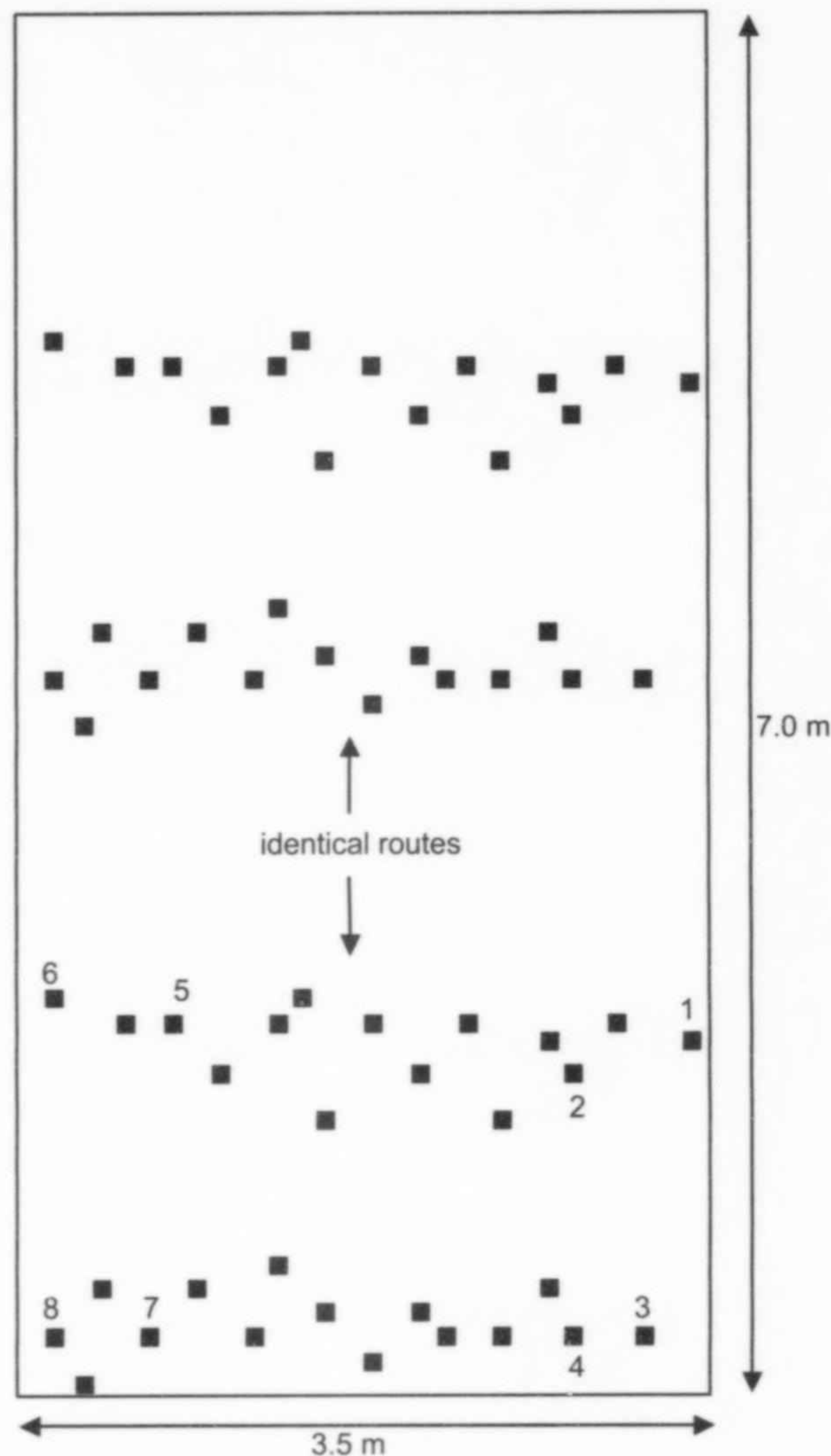


FIGURE 2 Front view of the climbing wall used in Experiment 2. The routes in the low and high condition are identical. The positions of the holds are indicated by black squares. Holds 1 through 4 indicate the starting position. See text for explanation of Holds 5 through 8.

strated that a traverse consisting of 11 holds sufficed to climb from left to right on the same climbing wall. As the same hold could be used multiple times in climbing a traverse, we operationalized the selection of action possibilities by counting the number of movements made to climb the traverse. In doing so, we distinguished between performatory movements and exploratory movements (E.J. Gibson, 1988). Performatory movements are meant to reach a certain goal, for instance, moving a hand or foot from one hold to the next to use it as support for further climbing actions. Exploratory movements are primarily information gathering

movements, for example, when a climber wants to explore whether a hold is within reach. We predicted that the participants would make both more performatory and more exploratory movements in executing the climbing task in the high-anxiety condition than in the low-anxiety condition.

Method

Participants. A total of 12 participants, 6 men and 6 women,⁵ mean age 20.8 years ($SD = 3.57$) volunteered to participate in the experiment. None of them had participated in Experiment 1. The participants, all college students, had no experience in climbing and were naive to the purpose of the experiment. All provided informed consent.

The mean trait anxiety score for the male participants was 34.8 ($SD = 4.26$), and was not significantly different from the mean score for Dutch male college students ($M = 36.1$, $SD = 8.4$) obtained by Van der Ploeg et al. (1980) on a t test between a sample and a population mean (Thomas & Nelson, 1996), $t(5) = 0.73$, ns . The mean trait anxiety score for the female participants was 34.0 ($SD = 5.66$), and was not significantly different from the mean score for Dutch female college students ($M = 37.7$, $SD = 8.4$; Van der Ploeg et al., 1980), $t(5) = 1.60$, ns . The results indicated that the participants had no extraordinary predisposition to respond across many situations with high levels of state anxiety (e.g., Smith et al., 1998).

Experimental setup. Participants climbed on the same climbing wall as that used in Experiment 1. Again, two identical horizontal routes were mounted low and high on the wall, each consisting of 15 footholds and 15 handholds (see Figure 2). The mean height of the footholds of the low traverse was 0.36 m (low-anxiety condition) whereas that of the high traverse was 3.69 m (high-anxiety condition). To enable participants to start climbing in the high condition, the stepladder was again used.

As in Experiment 1, participants wore well-fitting climbing shoes and a climbing harness connected to a climbing rope. The same security procedure as in Experiment 1 was used. All climbs were videotaped using an S-VHS camcorder (sampling rate of 50 Hz); participants' hand and foot movements were clearly visible. We used a stopwatch to determine climbing time (see Dependent Variables section for a definition of this variable).

State and trait anxiety were measured in the same way as in Experiment 1. We decided not to use heart rate as a measure of state anxiety because a higher heart rate in the high condition is also a reflection of physical strain. Increased climbing

⁵In both Experiments 2 and 3, mixed samples of men and women were tested. We checked whether there were significant differences between males and females on the state anxiety scores as well as the performance measures reported in Experiments 2 and 3. No significant effects involving gender were obtained.

time in the high-anxiety condition is a consistent and robust finding in studies like this one (cf. Pijpers et al., 2003, 2005).

Task execution. Participants were instructed to climb as fast and as safely as possible but it was stressed that the participant's first goal should be to complete the climbing task without falling. Each participant was told that a fall would immediately end the experiment, and that the participant would be excluded from the experiment and subsequent analyses. During the experiment, none of the participants fell. No instructions were given as to how to climb faster or which holds to use.

Procedure. Participants were tested individually on a single day. They were informed about the procedure of the experiment, after which participants signed an informed consent statement. They completed the Dutch version of the STAI A-Trait scale (Van der Ploeg et al., 1979).

After putting on their climbing shoes and harness, participants practiced climbing on the climbing wall. As the number of holds was more than sufficient to climb from the right side of the climbing wall to the left side and back again to the right side, all participants were able to successfully complete the practice task within a few minutes. As a consequence, the experimenters were confident that a participant's failure to complete the task in either condition was not due to lack of experience with the task.

After practice, participants were allowed 15 min to recuperate. Three minutes prior to running each condition, participants were positioned in front of the wall, either on the floor or the stepladder, depending on the condition in question. Two minutes before the climb, participants were asked to indicate how anxious they were at that moment by filling out an anxiety thermometer to familiarize themselves with the thermometer. Then, participants were connected to the safety rope. The camcorder was switched on and participants were instructed to begin when ready by assuming the starting position on the wall. A participant was considered to be in the starting position when he or she had placed the right hand on Hold 1, left hand on Hold 2, right foot on Hold 3, and left foot on Hold 4 (see Figure 2). As soon as participants had assumed the starting position in the high condition, the stepladder was quickly removed. In the low condition, participants were instructed not to start climbing immediately, but to wait just as long as it would have taken to relocate the stepladder in the high condition (less than 10 sec). In both conditions participants started climbing at a sign from one of the experimenters. Participants resumed the same position after they had climbed the traverse two times. Hence, participants climbed the traverse from the right to the left (ending with the right hand on Hold 5, left hand on Hold 6, right foot on Hold 7, and left foot on Hold 8; see Figure 2), and back to the right again. Immediately after the climb, the participants were asked to recall how anxious they had felt during the climb and to record this on the anxiety thermometer. This anxiety score was used as an anxiety score for that climb (and thus, for that condition).

After a recuperation period of at least .5 hr the procedure was repeated, but now participants climbed in the other condition (high if they had started low; low if they had started high). The order of high and low conditions was reversed with each new participant (balanced over male and female participants).

Dependent variables. For each condition, the following dependent variables were determined from the videotapes:

1. *Number of performatory movements*, defined as the number of movements during which a hold is released and contact is made with another hold, which is then used as support.
2. *Number of exploratory movements*, defined as the number of times a hold was touched without it being used as support.

Participants' movements were viewed by two independent raters for accurate determination of the dependent variables just mentioned. There was a 100% interobserver agreement regarding performatory as well as exploratory movements.

3. *Climbing time* was also registered for each condition; it was defined as the sum of the time needed to climb the two traverses (from the right to the left, and back). As soon as participants released one of the holds in the starting position, time started. When participants had returned to the starting position, the time was stopped.

Statistical analysis. See Experiment 1.

Results

State anxiety. Participants reported significantly higher anxiety scores in the high condition ($M = 4.8$, $SD = 1.81$) than in the low condition ($M = 2.2$, $SD = 1.98$), $t(11) = 5.32$, $p = .0001$, $ES = 1.33$, indicating that the anxiety manipulation was again successful.

Behavioral variables. Table 2 presents an overview of the results concerning number of performatory movements (hand and foot movements), number of exploratory movements, and climbing time. The number of performatory movements was significantly higher in the high condition than in the low condition, $t(11) = 3.00$, $p = .006$, $ES = 1.08$. Investigating hand and foot movements separately, it appeared that significantly more performatory hand movements were made in the high condition than in the low condition, $t(11) = 3.90$, $p = .001$, $ES = 1.21$, as well as significantly more performatory foot movements, $t(11) = 2.11$, $p = .029$, $ES = 0.76$. Also the number of exploratory movements was significantly larger in the high condition than in the low condition, $t(11) = 2.76$, $p = .009$, $ES = 1.14$. Both the number of exploratory hand movements and the number of ex-

TABLE 2
 Number of Performatory Movements, Number of Exploratory
 Movements, and Climbing Time^a for the Conditions in Experiment 2

Variable	Condition			
	Low-Anxiety		High-Anxiety	
	M	SD	M	SD
Number of performatory movements	40.0	5.80	47.5	7.97
Hand movements	20.9	3.18	24.8	3.30
Foot movements	19.1	3.75	22.7	5.69
Number of exploratory movements	1.3	2.10	6.3	6.67
Hand movements	0.9	1.44	5.1	5.74
Foot movements	0.4	1.00	1.3	1.22
Climbing time	45.8	12.8	78.8	25.4

^aIn sec.

ploratory foot movements were higher in the high-anxiety condition than in the low-anxiety condition, $t(11) = 2.47$, $p = .016$, $ES = 1.59$, and $t(11) = 2.80$, $p = .009$, $ES = 0.75$, respectively.

It appeared that climbing time increased significantly from 45.8 sec in the low condition to 78.8 sec in the high condition, $t(11) = 5.62$, $p < .0001$, $ES = 1.73$. There were large individual differences in climbing time, causing the large standard deviations. In the low condition, climbing time ranged from 27 to 69 sec, and in the high condition from 54 to 143 sec.

Discussion

As expected, in the high-anxiety condition, the abundance of alternatives to climb the traverse (provided by more holds) resulted in more movements, both performatory and exploratory. This indicates that a person's internal state plays a role in perceiving and realizing action possibilities: Across anxiety conditions, participants selected different action possibilities from the plethora of action possibilities afforded by the environment.

In Experiment 1 it was found that changes in perceived and actual maximal reaching height occurred due to anxiety. These changes may partly account for the effects observed in Experiment 2. However, it is questionable whether the differences in perceived and actual reachability, which were in the order of magnitude of several centimeters, can fully explain why participants made so many more (performatory and exploratory) movements in the high-anxiety condition than in the low-anxiety condition. Note that using more holds implies shifts in grasping distance of (at least) 17 cm, as the holds were 17 cm apart in vertical direction and 24 cm in horizontal direction, whereas changes in perceived and actual abilities were

"only" a few centimeters. It may be that on top of the changes in perceived and actual maximal reaching height, anxiety induced changes in participants' detection of relevant information for climbing, that is, in attention. Shifts in attention have been identified as one of the key mechanisms underlying changes (mostly decrements) in performance due to anxiety (Baddeley, 1972; Beilock & Carr, 2001; Janelle, Singer, & Williams, 1999; Landers, Wang, & Courtet, 1985; Liao & Masters, 2002; Mullen et al., 2005; Weltman & Egstrom, 1966; Weltman, Smith, & Egstrom, 1971). As attentional mechanisms might underlie the anxiety-induced changes in perception and realization of action possibilities that were found in Experiments 1 and 2, a third experiment was conducted to examine the relation between anxiety and attention in the climbing task.

EXPERIMENT 3

Two major accounts have been suggested in the literature to explain changes in attention due to anxiety (see Beilock & Carr, 2001; Janelle et al., 1999; Moran, Byrne, & McGlade, 2002). First, Easterbrook's (1959) cue-utilization theory states that as one experiences greater anxiety, the attentional field narrows (cf. Bacon, 1974; Janelle et al., 1999; Williams & Elliott, 1999). As a result, performance on central tasks will first be facilitated at the expense of performance on peripheral tasks, as peripheral (irrelevant) information will be blocked. At even higher anxiety levels, this funneling effect may also prohibit attention to the information sources relevant for the central task, resulting in a decrement in performance on this central task. Second, performance decrements under stressful conditions can also be explained by the notion that anxious people are more easily distracted (Eysenck, 1992; Janelle et al., 1999). Within the distraction models, it is proposed that some stimuli shift attention away from task-relevant information to task-irrelevant cues, thereby decreasing performance (see also Moran, 1996). It is assumed that increased pressure will cause individuals to focus on distracting stimuli either externally (e.g., crowd noise) or internally (e.g., worries) instead of focusing on task execution *per se*.

Although originating from an information-processing approach, attentional narrowing and distraction are not necessarily inconsistent with an ecological perspective. In ecological terms, attentional narrowing would imply missing less useful or nonspecifying information⁶ when anxiety increases. When anxiety increases

⁶A nonspecifying information source may be related to a to-be-perceived property, but it is not specific to it, as its value does not under all circumstances reliably predict the value of the to-be-perceived property (Beek, Jacobs, Daffertshofer, & Huys, 2003). Specifying information sources are specific to (to-be-perceived) properties of the environment. This means that detecting a certain information source that specifies a property of the environment allows the observer to make reliable judgments about this property (Beek et al., 2003).

further, one might even start missing task-specific, specifying information, as a result of which the performance of the main task would be hampered.

Distraction would imply changes in the degree to which useful and less useful information draw the actor's attention. In terms of ecological psychology, there are changes in the "attensity" of information surrounding the actor, with *attensity* defined as "a measure of the attraction that an area of information has for a perceiver" (Michaels & Carello, 1981, p. 71).

Based on the results of Experiments 1 and 2, one would expect that, of these two mechanisms, attentional narrowing in particular would play a role high on the climbing wall. Therefore, in Experiment 3, we again asked novices to perform a climbing task in low-anxiety and high-anxiety conditions. In both conditions, participants now simultaneously had to respond as quickly as possible to the appearance of a series of red lights projected on the climbing wall. If, as expected, attentional narrowing were to occur, participants would focus more on the primary climbing task and consequently detect fewer projected lights in the high-anxiety condition than in the low-anxiety condition, or they would at least respond more slowly to the detected lights if the number of detected lights remained the same. If, contrary to our expectations, (external) distraction were to prevail (implying enhanced susceptibility to peripheral distractors, Williams & Elliott, 1999), one would expect that, in the high-anxiety condition, participants would detect the same number or more projected lights with the same or a quicker response time than in the low-anxiety condition.

Method

Participants. A total of 17 participants, 5 men and 12 women, mean age 21.4 years ($SD = 2.42$) volunteered to participate in the experiment. The participants, all college students, had no experience in climbing and were naive to the purpose of the experiment. None of them had participated in Experiments 1 or 2. All provided informed consent.

The mean trait anxiety score for the male participants was 28.6 ($SD = 4.93$) and was significantly lower than the mean score for Dutch male college students ($M = 36.1$, $SD = 8.4$) obtained by Van der Ploeg et al. (1980) on a t test between a sample and a population mean (Thomas & Nelson, 1996), $t(4) = 3.40$, $p < .05$. The mean trait anxiety score for the female participants was 33.8 ($SD = 7.52$), and was not significantly different from the mean score for Dutch female college students ($M = 37.7$, $SD = 8.4$, Van der Ploeg et al., 1980), $t(11) = 1.80$, ns . The results indicated that the participants had no extraordinary predisposition to respond across many situations with high levels of state anxiety (e.g., Smith et al., 1998).

Task execution. Participants were instructed to climb as fast and as safely as possible; however, their primary goal was to complete the climbing task without falling. They were told that a fall would immediately end the experiment, and that

the participant would be excluded from the experiment and subsequent analyses. Participants had to climb the traverse four times—that is, starting at the left side of the wall, the participants climbed to the right side (Traverse 1), then returned to the left side (Traverse 2), back again to the right side (Traverse 3), and back again to the left side of the wall (Traverse 4). It was also emphasized that participants should say out loud “Yes” as quickly as possible when they observed a red light that was projected on the climbing wall. Participants were informed that both tasks were equally important in terms of the overall performance score.

During the experiment, none of the participants fell. No instructions were given with respect to how to climb faster, or which holds to use.

Experimental setup. Participants climbed on the same climbing wall as that used in Experiments 1 and 2. Again, two identical horizontal routes were mounted low and high on the wall, each consisting of five footholds and six handholds (see Figure 3). The mean height of the footholds of the low traverse was 0.34 m (low-anxiety condition), whereas that of the high traverse was 3.68 m (high-anxiety condition). To enable participants to start climbing in the high condition, the stepladder was again used (see Experiments 1 and 2).

For the peripheral light detection task, laser lights were projected on the climbing wall in the vicinity of the participants while they were climbing the traverse. For this purpose, we developed a so-called laser pointer system (LP system; see Figure 4). The LP system consisted of a box with five laser pointers attached to it. There were four peripheral pointers and one central pointer. The LP system was placed on a 1.31-m-high tripod at a distance of 7 m from the climbing wall. The laser pointers could be moved around a ball-and-socket joint to adjust the direction of the light beam and hence the projection of the lights on the climbing wall. With a handle attached to the LP system, the central laser pointer (labeled “ML”, i.e., marker light; see Figure 4) could be moved up and down, and from the right to the left, making it possible to direct it continuously on a marker on the participant’s back while he or she was climbing on the wall. Consequently, the four peripheral laser pointers projected their lights at (almost) the same distances from the participants irrespective of their climbing actions. In the high condition, the LP system was directed upward, and the angles of the laser beams were adjusted to keep the positions of the lights relative to the participant identical to those in the low condition.

The locations of the peripherally projected lights were (see Figure 4): right of the right shoulder (labeled “RS”), left of the left shoulder (labeled “LS”), right of the right hip (labeled “RH”), and left of the left hip (labeled “LH”). The LP system was connected with a PC. By means of a specially developed software program (LabVIEW; Version 6.1; National Instruments; Austin, Texas) it was possible to set the frequency, duration, and order of light activation of the laser pointers. During Traverses 1 and 3, the order of the lights projected on the climbing wall was set as follows: RS, RH, LH, and LS. During Traverses 2 and 4 the order was LS, RH, LH,

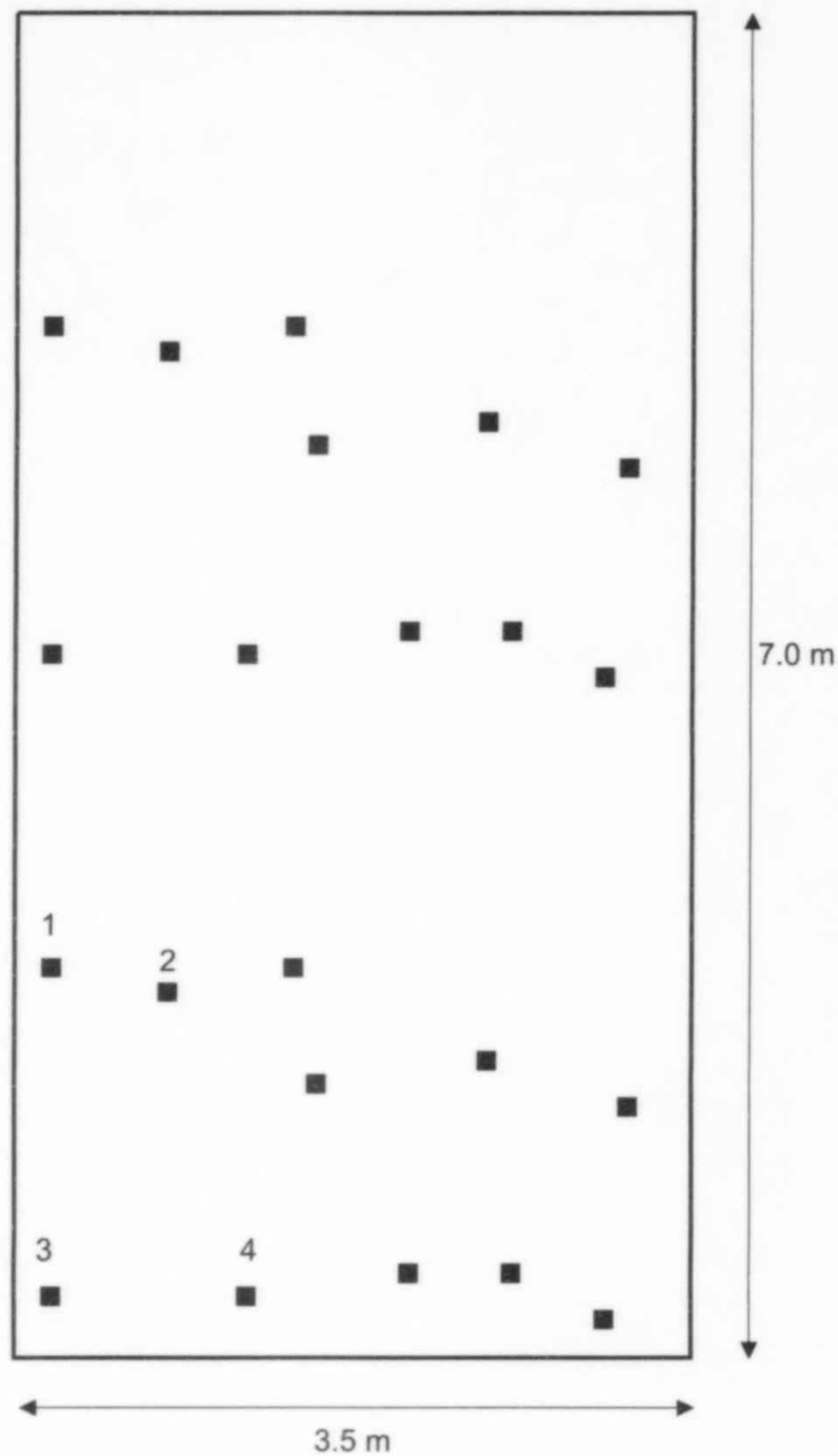


FIGURE 3 Front view of the climbing wall used in Experiment 3. The routes in the low and high condition are identical. The positions of the holds are indicated by black squares. Holds 1-4 indicate the starting position.

and RS. Every 3.5 sec a light was projected on the wall for 500 ms. The windows in the laboratory were blinded so that the light intensity was constant during the testing period. A stickpin microphone (also connected to the computer) with a basic amplifier was used to pick up the participant's "Yes" to calculate his or her response time (see also the Dependent Variables section). The software also provided a graphical representation of the moments laser pointers were switched on and off (and which laser pointer), and participants' verbal responses to the appearance of the lights (by means of whimsical bursts in the output signal).

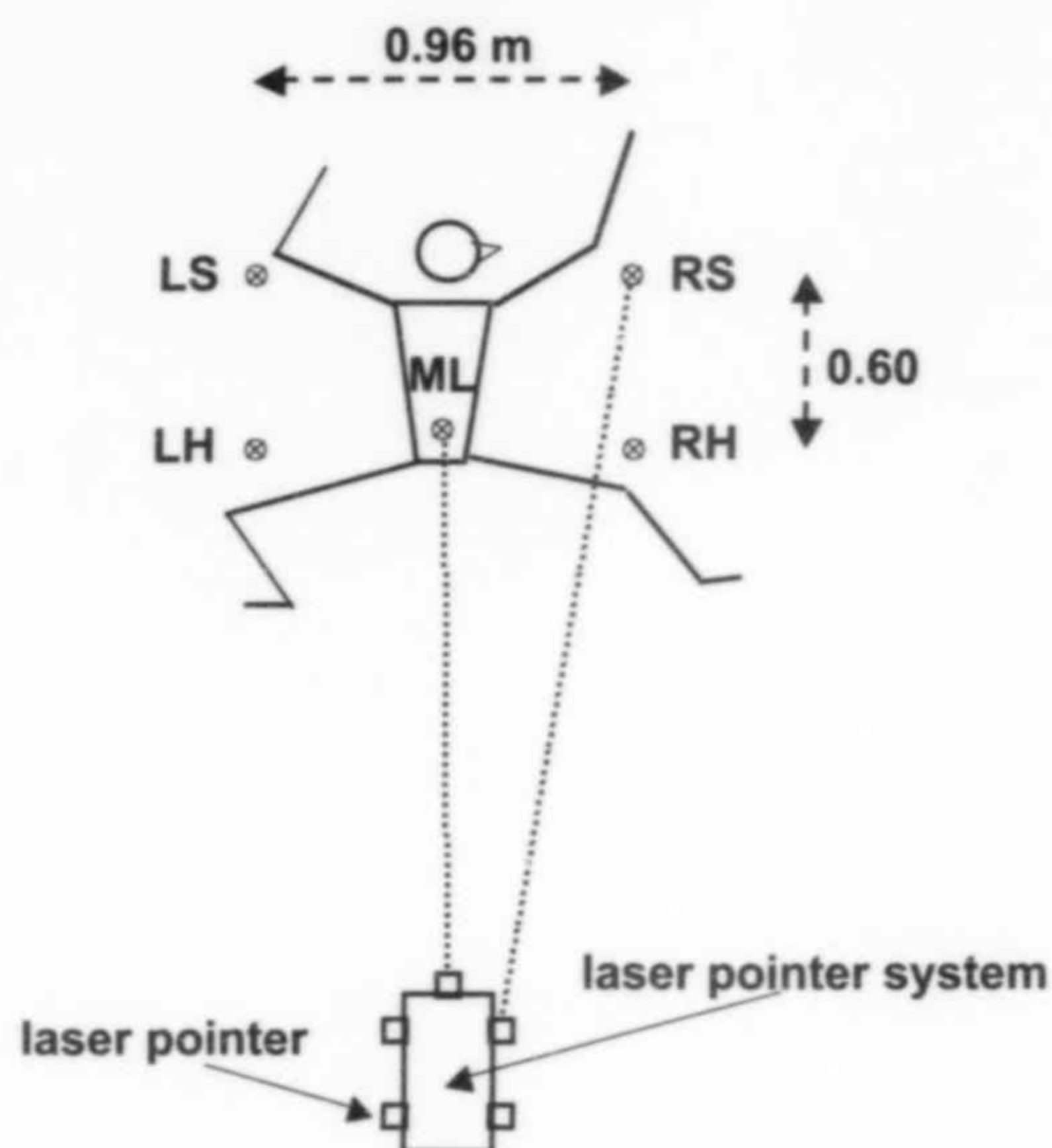


FIGURE 4 Projection of the four peripheral lights on the climbing wall (LS = left shoulder, LH = left hip, RS = right shoulder, and RH = right hip). The central pointer (ML = marker light) was continuously directed at the marker on the participant's back.

As in Experiments 1 and 2, participants wore well-fitting climbing shoes and an integral harness connected to a climbing rope. The same security procedure as in Experiments 1 and 2 was used. All climbs were videotaped using an S-VHS camcorder (sampling rate of 50 Hz). The camcorder was placed next to the LP system. State and trait anxiety were measured in the same way as in Experiment 2.

Procedure. Participants were tested individually on a single day. The entire procedure was explained to each participant, and questions concerning the experiment were answered. Participants were then asked to read and sign an informed consent statement. After each participant had completed the Dutch version of the STAI A-Trait scale (Van der Ploeg et al., 1979), the microphone was placed, and the participant put on climbing shoes and a harness. The participant then practiced the low traverse until he or she was able to climb the traverse two times back and forth. Practice periods lasted about 5 to 10 min. Then the lights were presented on the climbing wall after the participant had taken position on the wall to (a) familiarize the participant with the procedure and (b) make sure that the lights fell within his or her peripheral visual field, which was the case for all participants. After this, participants were allowed to pause for at least 15 min.

Subsequently, the participants' task was explained in detail: specifically, they were told that the climbing task had to be carried out as fast and safely as possible, and that at the same time they had to say out loud "Yes" as quickly as possible each time they observed a red light. One minute before the climb participants were

asked to indicate how anxious they were at that moment by completing the anxiety thermometer, again for the purpose of familiarization. The participant was then led to the climbing wall and connected to the rope. The camcorder was switched on, and the participant was asked to take position on the wall: The participant placed the left hand on Hold 1, right hand on Hold 2, left foot on Hold 3, and right foot on Hold 4 (starting position; see Figure 3). As soon as participants had assumed the starting position in the high condition, the stepladder was quickly removed. In the low condition, participants were instructed to not start climbing immediately, but to wait just as long as it would have taken to reposition the stepladder in the high condition (less than 10 sec). In both conditions participants started at a sign from one of the experimenters. They then climbed the traverse four times.

Immediately after each condition, participants were asked to recall how anxious they had felt *during* climbing and to record this on the anxiety thermometer scale. This was used as anxiety score for the condition in question. High and low conditions were counterbalanced.

The participant was allowed a recuperation period of about 30 min before starting the second condition. No feedback about his or her performance was given. The second condition was executed in a similar fashion as the first, but now the participant climbed in the other condition (low if the participant had started high, high if he or she had started low).

Dependent variables. For each condition the following dependent variables were determined:

Number of detected lights, defined as the number of lights observed by the participant during climbing.

Response time, operationalized as the time between switching on a laser pointer and the participant's verbal response to it.

Climbing time, defined as the time needed to climb the traverse four times. Climbing time started as soon as the participant had left the starting position and stopped as soon as the participant had resumed the starting position after climbing the traverse four times. Climbing time was determined from the videotape.

Statistical analyses. See Experiment 1.

Results

State anxiety. Participants had significantly higher anxiety scores in the high condition ($M = 5.0$, $SD = 2.56$) than in the low condition ($M = 2.4$, $SD = 2.40$), $t(16) = 4.23$, $p = .0003$, $ES = 1.04$. Thus, the manipulation of anxiety was again successful: participants were more anxious in the high condition than in the low condition.

Performance on the climbing task. As in our previous studies (Pijpers et al., 2003, 2005), the climbing time in the high condition ($M = 107.5$ sec, $SD = 27.10$) was significantly longer than in the low condition ($M = 88.4$ sec, $SD = 16.58$), $t(16) = 4.66$, $p = .0001$, $ES = 0.88$. There were large individual differences in climbing time: In the low condition climbing time ranged from 69 to 137 sec, and in the high condition from 73 to 175 sec.

Performance on the light detection task. Due to differences in the average climbing times, the average number of lights that could be detected was 26.9 ($SD = 6.78$) in the high condition and 22.1 ($SD = 4.15$) in the low condition. Nevertheless, participants detected, on average, significantly fewer lights in the high condition ($M = 3.7$, $SD = 3.10$) than in the low condition ($M = 6.5$, $SD = 3.47$), $t(16) = 3.51$, $p = .001$, $ES = 0.85$. To diminish the confounding effect of climbing speed, we first determined which lights could have been detected by each participant. As the fastest participant needed 69 sec to execute the task—that is, about 17 sec per traverse—this participant could maximally have detected four lights per traverse. Therefore, we determined for each participant which lights were detected of the first four lights that were presented in Traverse 1, Traverse 2, Traverse 3, and Traverse 4. Each participant, including the fastest, could, in principle, have detected these first four lights per traverse, thus, 16 in total. Also according to this analysis, participants detected significantly fewer lights in the high-anxiety condition ($M = 2.2$, $SD = 1.64$) than in the low-anxiety condition ($M = 4.6$, $SD = 1.91$), $t(16) = 4.86$, $p < .0001$, $ES = 1.35$.

The 16 lights that could have been detected by all participants can be classified into lights that were presented in the direction of locomotion (the so-called ahead detections), and lights that were presented in the opposite direction (the so-called behind detections). A 2 (Height: low condition, high condition) $\times$ 2 (Direction of locomotion: ahead, behind) repeated measures ANOVA on the detection data revealed a significant main effect of height, $F(1, 16) = 23.57$, $p < .001$, $ES = 1.33$, $\eta^2 = .60$, and a significant main effect of direction of locomotion, $F(1, 16) = 41.43$, $p < .001$, $ES = 1.43$, $\eta^2 = .72$, indicating that, on average, significantly more ahead lights were detected ($M = 2.6$, $SD = 1.59$) than behind lights ($M = 0.8$, $SD = 1.05$). The interaction between height and direction of locomotion was not significant, $F(1, 16) = 1.66$, $p = .22$.

The average response time was not significantly different between the high condition ($M = 742$ ms, $SD = 217.5$) and the low condition ($M = 774$ ms, $SD = 242.7$), $t < 1$.

Discussion

Findings generally confirmed the notion of attentional narrowing (Bacon, 1974; Easterbrook, 1959; see also Murray & Janelle, 2003) in that participants detected fewer lights in the high-anxiety condition than in the low-anxiety condition. Ap-

parently, in the high-anxiety condition attention was more narrowly focused on information relevant for climbing, whereas information that was less relevant for climbing at that moment (projected lights) was overlooked.

It should be noted that under anxiety the reduction in the number of lights detected occurred despite the fact that in the low-anxiety condition the number of lights detected was already low (about 25%). In the analyses presented in the preceding section, which were based on 16 lights (8 ahead and 8 behind lights), 43% of the ahead and 15% of the behind lights were detected in the low-anxiety condition. This indicates that "merely" climbing on the climbing wall is already attention consuming. In the high-anxiety condition only 23% of the ahead lights and 4% of the behind lights were detected, showing that almost all of the lights projected behind the climbers were missed and only a fourth of the lights projected in front of the climbers were detected.

In short, the results point in the direction of attentional narrowing because more lights went undetected in the high-anxiety condition. However, as Janelle et al. (1999) remarked, the mechanisms of attentional narrowing and distraction could be operative simultaneously. Instead of focusing on task execution *per se* (climbing and detecting lights), participants may have been focusing on internally distracting stimuli such as worries and negative thoughts (also) leading to the detection of fewer lights. Visual search data may shed more light on the precise changes that occur under anxiety in visually attending to specific locations on the climbing wall (cf. Murray & Janelle, 2003; Williams & Elliott, 1999).

GENERAL DISCUSSION

J.J. Gibson (1979/1986) suggested that the environment is perceived in actor-relevant terms, that is, in terms of what an actor can do with and in the environment. In keeping with this notion, research has shown that changes in one's potential to act influence the perception of action possibilities (e.g., Bhalla & Proffitt, 1999; Pijpers et al., *in press*; Proffitt et al., 1995). Based on that idea, we assumed that changes in the actor's emotional state that lead to changes in his or her action capabilities will also lead to changes in the perception of those action possibilities. Perception-action experiments on a climbing wall allowed us to investigate the influence of the actor's emotional state—*anxiety*—on perceiving and realizing affordances.

Experiment 1 demonstrated that anxiety reduced both perceived and actual maximal reaching height. Subsequently, in Experiment 2 and in line with the results of Experiment 1, anxiety was found to affect the realization of action possibilities, leading to the use of more holds on the same traverse. Experiment 3 particularly provided support for attentional narrowing as an additional underlying mechanism (on top of the reduction of perceived and actual maximal reaching height) of the anxiety-induced changes in realizing affordances, as found in Experi-

ment 2. Note that grasping holds that are easily within reach rather than at the maximum of one's reachability is consistent with attentional narrowing. If attention narrows, one is bound to grasp those holds that are closer and still within one's field of attention. Of course, these results do not discard the possibility that, in Experiment 2, the use of more holds reflects a more conservative and safer climbing strategy independent of attentional narrowing.

The findings of Experiments 1 and 3 indicate that anxiety affects the detection of information about the action possibilities in the environment, whereas the findings of Experiment 2 (and Experiment 1) suggest that anxiety constrains the realization of action possibilities. In our view, these findings suggest how, from an ecological point of view, the perception and realization of affordances might be understood in situations in which emotional processes are in play.

As an entry point to discussing the theoretical implications, it is useful to first turn to the results of Jiang and colleagues (Jiang & Mark, 1994; Jiang, Mark, Anderson, & Domm, 1993) on the perception of gap crossability. They found that, when individuals had to judge whether they could step over a gap, their estimates of crossable gap width decreased as gap depth increased. This finding seems to refer to a process similar to that addressed in this study in that increased gap depth led to increased anxiety, which in turn affected the perception of gap crossing capability. However, Jiang and colleagues disputed that emotional processes were causing the more conservative assessments. They attempted to substantiate this claim by showing that estimates of gap crossing capability critically depended on where observers directed their gaze. When looking down into the gap, participants tended to underestimate their capabilities more than when they looked toward the horizon. This explanation, however, does not preclude the possibility that gaze direction and emotional processes covaried (cf. Janelle et al., 1999; Murray & Janelle, 2003; Williams & Elliott, 1999; Williams, Vickers, & Rodrigues, 2002), that is, when participants looked down into the gap, they may have felt some fear of the depth resulting from the increased risk to their safety. When they looked at the horizon, participants may have felt no fear or less fear. Hence, anxiety might have played a role in the observed changes in the perception of gap crossability.

In line with previous findings (e.g., Bhalla & Proffitt, 1999; Proffitt et al., 1995), we once more found support for the intricate relation between the perception and the realization of action possibilities. An observer who is in a threatening environment will pick up information about that environment as well as information about his or her own (emotional) state. The latter will deviate from ordinary feelings, sensations, and so forth, and the observer will behave accordingly. As such, the anxiety-induced bodily and physiological reactions are part and parcel of the properties of the animal-environment system in which affordances are perceived and realized. Many studies have reported all kinds of bodily changes under threatening conditions (e.g., Brooke & Long, 1987; Frijda, 1986; Weinberg & Hunt, 1976). Given the mutuality of observer and environment, it follows that changes in action capabilities will be detected, which will affect the individual's perception of

affordances. Using a similar setup to that used in this study, Pijpers et al. (2003) demonstrated considerable and significant increases in blood lactate concentration and muscle fatigue under anxiety. Evidently, the environment affected the neuromuscular system and participants accounted for these effects when asked to judge their maximal reaching height in that environment. Hence, anxiety-induced changes in action capabilities closely corresponded to changes in the perception and realization of affordances.

In conclusion, an actor's emotional state affects the perception and realization of affordances in a manner that is consistent with the changes that accompany this emotional state, such as changes in attention and actual action capabilities. Rather than portraying this emotional state as a spooky and subjective variable, this once more emphasizes the intricate relations between actor and environment and perception and action.

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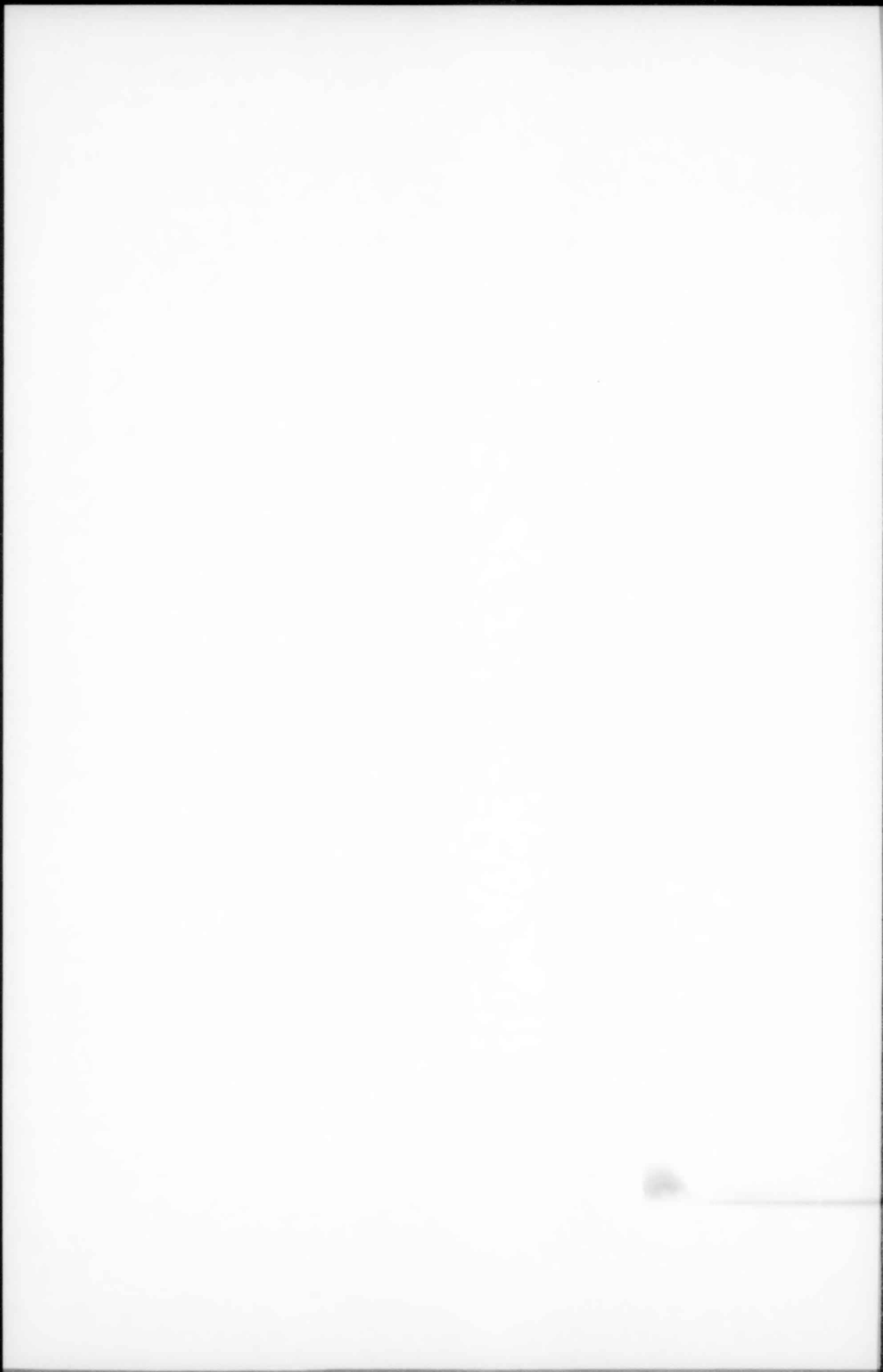
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Perceiving Affordances of Hockey Sticks by Dynamic Touch

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The haptic subsystem of dynamic touch is sensitive to the relation between a held object's distribution of mass and the object's affordances. In four experiments participants used dynamic touch to gauge the suitability of differently weighted hockey sticks for performing power (transferring maximal force) and precision (intercepting a moving object) actions. Results showed that perceivers could use dynamic touch to perceive the affordances of the hockey sticks. Perceptual sensitivity to action-relevant object properties was modified when novice participants were given the opportunity to discover subtle task constraints by actually performing the hockey tasks. Expert (collegiate-level) hockey players' ratings reflected attunement to the constraints that prompted changes in novices' responses.

In daily life, people frequently hold and manipulate objects such as pens, utensils, and sports implements (e.g., rackets or hockey sticks). When perceivers hold an object and use it to perform a given task, they are using muscular effort to overcome and control the object's inherent resistance to being moved (i.e., its inertia). This type of muscular exertion, in combination with stimulation of mechanoreceptors in the skin and other tissues, has been termed *kinesthetic touch* (Loomis & Lederman, 1986) or *dynamic touch* (J. J. Gibson, 1966). People's ability to successfully perceive object properties such as length and orientation implies that dynamic touch is capable of registering information that specifies those object properties. Research has shown that perceptions of a hand-held object using dynamic touch are constrained by the object's spatial distribution of mass, or, in other words, by the object's inertial properties (see Carello & Turvey, 2000, 2004; Turvey, 1996; Turvey & Carello, 1995).

Dynamic touch also allows users of implements to perceive the utility of a given implement for a given task—in other words, to perceive an implement's *affordances* (J. J. Gibson, 1979/1986), or the purposes for which the implement can be used by a given actor (Carello, 2004). A number of studies have investigated the perception of affordances by kinesthetic or dynamic touch (Bingham, Schmidt, & Rosenblum, 1989; Solomon & Turvey, 1988; Turvey, Shockley, & Carello, 1999; Wagman & Carello, 2001, 2003; Wagman & Taylor, 2004). The bulk of recent research on perceiving affordances by dynamic touch has been focused on the issue of tool use. Those studies were motivated, in part, by Kreifeldt and Chuang's (1979) observation that an object's moment of inertia (its resistance to rotational acceleration) is an important contributor to the "feel" of a tool. In accordance with that observation, Wagman and Carello (2001) found that people are sensitive to inertial characteristics of hand-held tools and that specific higher-order inertial properties (inertia ellipsoid volume, symmetry, and eigenvector orientation) constrained the perception of a tool's affordances by dynamic touch (see also Pagano & Turvey, 1998). They also demonstrated that people are able to choose a hand-held object (or identify where to grasp an object) to maximize its utility for either hammering or poking tasks. Their participants designated as the best hammers objects for which the mass concentration was farthest from the point of grasp and as the best pokers the object with the mass concentration closest to the point of grasp. The authors concluded that people are sensitive to how inertial properties are informative about an object's utility.

In subsequent research, Wagman and Carello (2003) found that participants tailored their choice of grasp position according to how they were required to use an object. Grasp position (relative to the location of an object's center of mass) affects the rotational inertia of the object. When power movements were emphasized over precision control, participants grasped so that the objects' mass was concentrated further from the point of grasp. When precision was emphasized, grasp positions were chosen that resulted in the objects' mass being concentrated closer to the point of grasp. In a later study, Wagman and Taylor (2004) found that task constraints (power vs. precision tasks) and grasp position interactively influenced the choice of striking location for hand-held objects, and, moreover, that the influence of those factors was related to variations in inertial characteristics of the objects. Bongers (2001) similarly found that perception of affordances of hand-held objects by dynamic touch is also constrained by the relation between the object and the user.

This research used the sport of ice hockey as a context for investigating the role of dynamic touch in the perception of affordances of hand-held implements. Sports such as tennis and hockey require players to use hand-held equipment while visually attending to aspects of the sport other than the hand-held object. The demands of those sports often require precise positioning of hand-held implements within very narrow temporal limits and wielding the implements in

such a way as to impart large amounts of force on small targets. Such sports thus provide an ideal context for investigating the fluidity of dynamic touch in subserving tool use and for investigating the processes of perceptual learning that are presumably related to skilled tool use (Lockman, 2000). Several studies along those lines have been conducted regarding users' perceptions of tennis rackets (Brody, 2000; Carello, Thuot, Anderson, & Turvey, 1999; Carello, Thuot, & Turvey, 2000), and have demonstrated that both novices and experts are sensitive to action-relevant racket properties such as the location of the racket's sweet spot.

In this study we investigated perceiver sensitivity to the affordances of hockey sticks for either *power* (transferring maximal force to a puck) or *precision* tasks (precisely controlling the stick to intercept a small, moving object; cf. Wagman & Carello, 2001). We manipulated the inertial properties of hockey sticks by weighting the sticks in different configurations. These manipulations had consequences for how the sticks were actually suited for performing power and precision tasks—a priori, by the laws of mechanics, a bottom-weighted stick allows the user to transfer more force from the stick to the puck, and a top-weighted stick (by virtue of its relatively lower rotational inertia) is easier to control and maneuver. By analogy, a sledgehammer is very effective for hammering but precise control of the weighted end is difficult when the hammer is grasped at the handle-end; if instead grasped at the weighted end, the hammer would be easier to control but comparatively ineffective for hammering.

The first aim of this project was to determine whether perceivers could perceive the affordances of the hockey sticks, that is, whether participants could produce accurate judgments of the suitability of differently weighted hockey sticks for power or precision tasks (Experiment 1). We expected that participants could perceive the affordances of a hand-held implement for power and precision actions—in other words, that their ratings would accurately reflect the utility of the differently weighted sticks for the power and precision tasks (cf. Wagman & Carello, 2001). A novel feature of our research is that wielding a hockey stick is a bimanual action. Two-handed wielding requires coordinating the activities of the two hands and requires the two hands to function, in a sense, as a single perceptual device, even though the two hands grasp the hockey stick at spatially distinct points along the stick's length. Previous research on dynamic touch has almost exclusively focused on unimanual wielding (typically using smaller objects). Carello, Shockley, Harrison, Richardson, and Turvey (2003) examined bimanual wielding, but only in the case when the two hands were used in an overlapping grasp (one hand on top of the other).

The second aim was to determine the effects of perceptual-motor experience on affordance perception. More specifically, we were interested in the effects of exploratory or information-generating activity (Bingham et al., 1989; Oudejans, Michaels, Bakker, & Dolné, 1996) and perceptual learning (e.g., E. J. Gibson & Pick, 2000). In Experiment 2 we hypothesized that actually performing power

and precision tasks with the hockey sticks would enhance participants' preferences for the differently weighted sticks—bottom-weighted sticks would be more clearly favored for the power task, and top-weighted sticks for the precision task. Experiment 3 was conducted to test an alternative hypothesis that was formulated after obtaining unanticipated results in Experiment 2. Experiment 4 was conducted to determine the effects of hockey expertise on perceptual sensitivity to the suitability of the differently weighted hockey sticks for power and precision tasks. Carello et al. (1999) found that expert tennis players were generally no more accurate or reliable than novices at identifying the location of a racket's or a rod's sweet spot or at perceiving racket or rod length. However, although it is the case that the location of a racket's sweet spot (and, to a lesser extent, the racket's length) has consequences for the control of action when using the racket, the perceptual judgments obtained by Carello et al. were not explicitly formulated as affordance judgments, nor were their participants required to rate the utility or suitability of the rackets or rods for striking a ball. The role of expertise in perceiving the affordances of an implement for particular types of tasks thus remains unknown. We expected that expert hockey players would be attuned to the properties of hockey sticks that reflect the demands of precision and power actions in the context of ice hockey.

EXPERIMENT 1

Previous research has suggested that the perceived affordances of a held object for *hammering* and *poking* are influenced by the object's mass distribution (e.g., Wagman & Carello, 2001, 2003). Those authors found that a *poking* action was best served by an object whose mass was concentrated nearest the point of grasp. In contrast, the best *hammer* was characterized by a mass concentration furthest from the point of grasp. In Experiment 1, we determined whether perceptions of the functionality of a hockey stick would similarly depend on the stick's mass distribution. Participants wielded the hockey sticks with two hands and then rated the sticks (which were weighted at different points along their lengths) for their suitability for performing either a forceful movement (*power* condition) or a precision maneuver (*precision* condition). The power-hitting and precision-interception conditions were designed to parallel the hammering and poking conditions employed by Wagman and Carello, in that both hammering and power hitting emphasize the transfer of power and both poking and precision interception require fine control over the held object and maneuverability. If people are capable of perceiving the sticks that optimally afford power hitting and precision interception, then the manipulation of mass distribution should have a systematic effect on participants' ratings of the sticks for power and precision tasks: Hockey sticks with a mass concentration furthest from the point of grasp (greater moment of inertia) should be preferred for exerting force, whereas sticks with a

mass concentration closest to the point of grasp (lower moment of inertia) should be perceived as most suitable for conducting highly controlled or precision movements. In Experiment 1 we sought to extend the paradigm of Wagman and colleagues into a new task domain, hockey, and to the case of bimanual perception-action in which the two hands functioned as a single perceptual device. This allowed us in subsequent experiments to address the role of perception-action experience in perceiving affordances by dynamic touch, an issue that received only scant attention (and yielded null results) in previous research on dynamic touch and the affordances of hand-held tools (Wagman & Carello, 2001, Experiment 3).

Method

Participants. Twelve men and one woman participated. They were University of Cincinnati undergraduates enrolled in an introductory psychology course and they fulfilled a course requirement by participating. They ranged in age from 18 to 27 years ($M = 20.0$ yrs; $SD = 3.0$ yrs) and averaged 179.4 cm in height ($SD = 7.6$ cm). One participant reported playing recreational street hockey on occasion as a child, but was not involved in competitive or organized hockey. All other participants had no hockey experience whatsoever. The participant who played street hockey did not exhibit a distinct pattern of results compared to the other participants, so his data were included in all analyses. Participants did not have a history of disease or malfunction of their neuromuscular, vestibular, or skeletal system. Participants in all experiments signed an approved informed consent document.

Apparatus. Participants held and wielded three differently weighted, right-handed, Nike Quest 2 wooden hockey sticks (see Figure 1). The sticks were 162 cm long and were composed of fiberglass-wrapped solid aspen. Two 100 g metal weights were attached to the shaft of each stick using adhesive at one of three locations, yielding three unique mass-distribution conditions.¹ Pilot testing revealed that the three differently weighted sticks were distinguishable by dynamic touch. The added weights were placed at locations along the shaft of the sticks that would have produced approximately equal changes in the location of the center of percussion (CP) of straight, uniformly dense sticks of comparable size to the hockey sticks. Research has shown that people are haptically sensitive to the location of

¹Because we used commercially available sticks that were irregularly shaped and were not uniformly dense, and because the two-handed grip complicated determination of the point of rotation, it was difficult to accurately estimate the inertial properties of the sticks. For this reason, and because precise estimates of those quantities were not necessary to address the aims of this project, we did not compute estimates of the sticks' inertial properties. We refer to mass location conditions in qualitative terms (top-, middle-, and bottom-weighted stick conditions) rather than using quantitative descriptors such as moments of inertia, eigenvector orientation, or inertia ellipsoid volume or symmetry.

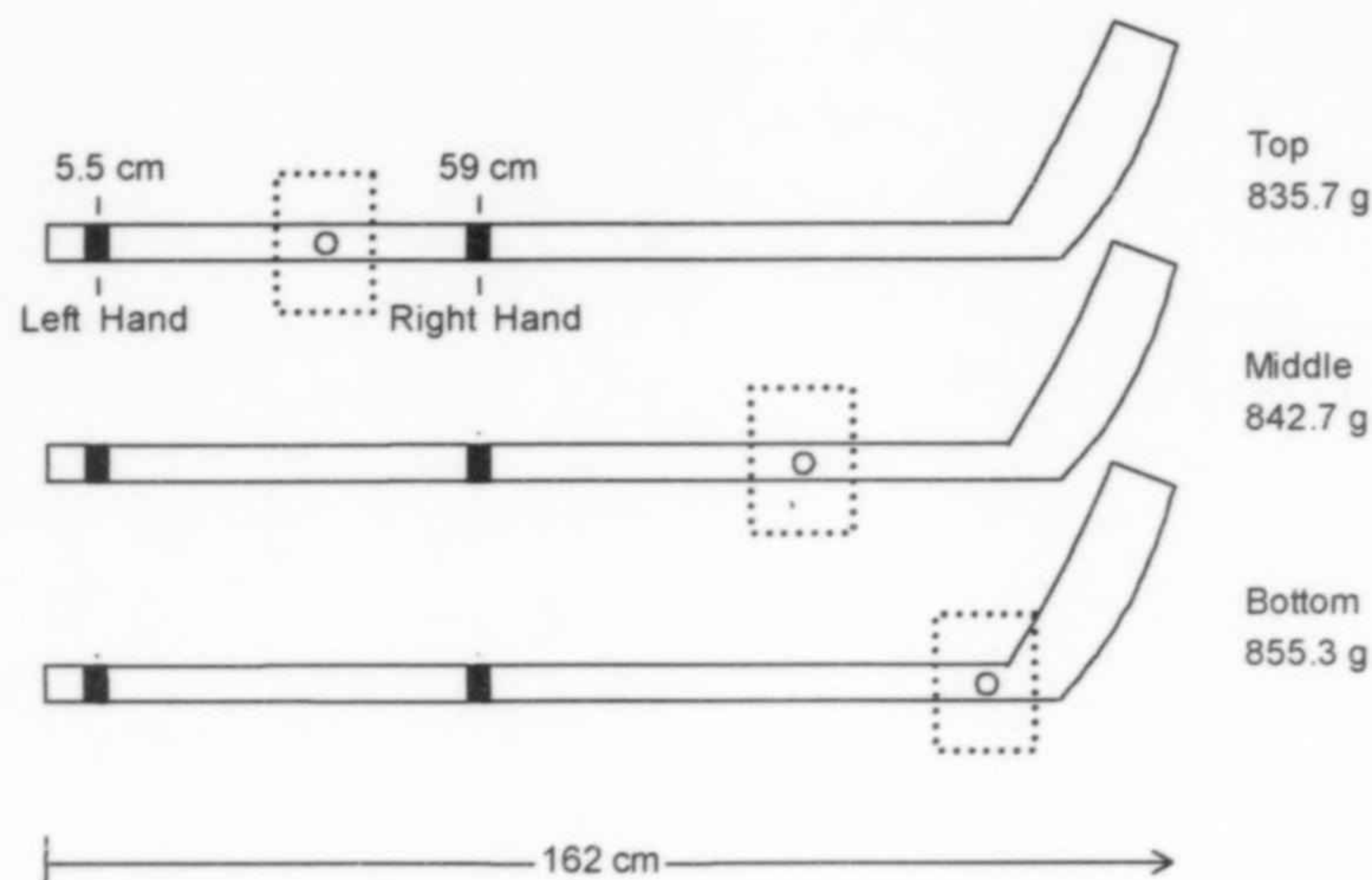


FIGURE 1 The top-, middle-, and bottom-weighted sticks used in all experiments. A 200-g weight was attached to the shaft of the stick at locations 41 cm, 111 cm, and 137 cm from the proximal end of the stick for the top, middle, and bottom sticks, respectively. Foam cubes masked the weight locations (hatched outline) in Experiments 2–4.

the CP of uniformly dense wooden rods and of tennis rackets (Carello et al., 1999; Carello et al., 2000).

To mask the weight location, low-density foam blocks were taped around all three potential weight locations, regardless of the actual weight location, so that the sticks were visually identical. To demarcate grasp location on the sticks, two pieces of Velcro were adhered to each stick at a position 5.5 cm (left hand) and 59.0 cm (right hand) from the top end of the stick (i.e., the nonbladed end). The soft, “loop” side of the Velcro was used for this purpose.

Procedure. The experiment was conducted in a large, open room that was of sufficient size to allow participants to freely swing a hockey stick. Participants wielded and rated each stick for its suitability for power or precision action with their eyes closed. In contrast to most previous research on dynamic touch, participants held and wielded the hockey sticks with two hands. The Velcro strips indicated the grasp location for the right and left hands and provided the tactile feedback necessary to locate the correct grip position without the use of vision. Participants closed their eyes, wielded a given stick for as long as they deemed necessary, and then verbally rated the stick using a 7-point scale from 1 (*not at all suited to the task*) to 7 (*ideally suited to the task*). Participants were encouraged to employ the full range of the rating scale to accurately reflect their perceived differences in utility among the sticks for the given task. The same scale and verbal rating method were used by Wagman and Carello (2001) to assess the perceived suitability of rods for power and precision tasks. In later research,

Wagman and colleagues replaced the verbal rating method with a method that required participants to choose the location of grasp position (Wagman & Carello, 2003) or point along the object at which optimal contact with a target object could be made (Wagman & Taylor, 2004) for power and precision tasks. The results of those later studies were consistent with the results obtained using verbal ratings. In Wagman and Carello (2001), participants tended to rate distally weighted objects as superior for hammering; in Wagman and Carello (2003) if participants were asked to grasp an object to use for power hammering they tended to grasp the object in such a way that the mass of the object was distally concentrated. These results suggest that the verbal rating method, despite being somewhat unsophisticated, possesses validity.

In the power condition participants were asked to make judgments of the suitability of each of the three modified hockey sticks for transferring power to a struck object. That is, they were asked to rate the sticks on the degree to which they could swing the stick to generate the most force. For the precision rating task, participants were asked to rate the sticks on the degree to which they could accurately maneuver them. They were asked to consider maneuverability when using the stick's blade to intercept an object moving past them, and to rate the degree of ease with which they could maneuver or position the stick's blade to make a quick and accurate interception. Participants did not actually use the sticks to perform power or precision tasks that involved striking another object.

Design and data analysis. Rating condition (power vs. precision) order was blocked and counterbalanced across participants. The order in which participants wielded the sticks was randomized within blocks. There were two rating conditions (power and precision) and three mass distribution conditions (mass at the top, middle, or bottom of the hockey stick), yielding six total conditions. Four repetitions per condition yielded 24 trials. Stick ratings were averaged across repeated trials in each condition for each participant. The two rating conditions (power and precision) were assessed separately using two repeated-measures analyses of variance (ANOVAs).

Results

Power task. The means and standard deviations of the ratings of the top, middle, and bottom mass location conditions were, respectively, $M = 3.22$, $SD = 1.33$; $M = 5.06$, $SD = 0.89$; and $M = 5.39$, $SD = 1.43$. A repeated-measures ANOVA revealed a statistically significant main effect of mass location, $F(2, 24) = 9.05$, $p < .01$, Cohen's effect size (Cohen, 1977) = 0.97. There was a trend for participants to favor the bottom-weighted stick. Bonferroni-Dunn post hoc comparisons revealed significant differences between ratings of the top- and bottom-weighted sticks, $p < .001$, and between ratings of the top- and middle-weighted sticks $p < .01$, but not between the middle- and bottom-weighted sticks, $p > .05$.

Precision task. The means and standard deviations of the ratings for the top, middle, and bottom mass location conditions were, respectively, $M = 6.28$, $SD = 0.70$; $M = 4.03$, $SD = 1.42$; $M = 3.12$, $SD = 1.20$. A repeated-measures ANOVA revealed a significant main effect of mass location, $F(2, 24) = 82.18$, $p < .001$, $f = 2.62$. Participants preferred the top-weighted stick for the precision task. All three pair-wise comparisons were significant, $p < .001$, according to Bonferroni-Dunn post hoc tests.

Discussion

The results of Experiment 1 were consistent with the hypothesis that was formulated based on the findings of Wagman and Carello (2001, 2003). Participants preferred the stick with the mass concentrated furthest away from the point of grasp when determining the stick's usefulness for exerting force. In contrast, participants preferred the stick with a mass distribution concentrated nearest the point of grasp when rating the sticks' usefulness for a precision control task. Those preferences were in accordance with the actual utility of the differently weighted sticks for power and precision tasks—the bottom-weighted stick would allow the user to transfer more force from the stick to the puck, and the top-weighted stick (by virtue of its relatively lower rotational inertia) would be easier to control and maneuver. Even though participants in this investigation did not have ice hockey playing experience (with the exception of one participant who played recreationally as a child), they were able to identify the mass distribution that would function best under each task condition.

The similarity of the results of this study to those of Wagman and Carello (2003) stems from the underlying similarity of the constraints of the tasks for which the objects were rated. Both Wagman and Carello's hammering condition and the power condition of this experiment reflected tasks that maximize the transfer of force using a held object or tool. The poking and precision conditions both reflected tasks constrained by the directed, precise application of force with a held tool. Both studies demonstrated people's ability to use dynamic touch to discriminate objects with reference to the force and precision control requirements of different tasks, based on variations in the objects' mass distributions. This study represented an extension of that work by generalizing the experimental paradigm to two-handed wielding, in which the two hands function as a single perceptual device.

These results were also consistent with Wagman and Carello's (2003) results in that they indicated an object's resistance to rotation, which depends directly on the object's mass distribution, is an informative variable on which to base perceptions of the object's utility for different behaviors. In other words, perceptions of a hand-held object's affordances may be based on how the object resists the exploratory wielding actions that perceivers undertake during dynamic touch (e.g., Carello & Turvey, 2004; Turvey & Carello, 1995; Turvey, 1996). For both

the power and precision conditions the manipulation of mass location produced strong effects on the perceptual reports. The observed specificity of the perceived affordances of the hockey sticks to the sticks' rotational inertia is consistent with previous studies indicating that a wielded object's affordances have a material basis in the spatial distribution of the mass of the stick. Therefore, accurate perception of those affordances should also vary as a function of the stick's mass distribution.

Whereas participants in this experiment were able to identify which mass distribution would function best under the power and precision conditions, they were not given the opportunity to actually perform those actions with the hockey sticks—they wielded the sticks, but did not engage them in an actual task-relevant action. Doing so may serve to fine-tune their ratings. Experiment 2 was designed to assess whether performing a task-relevant action would influence perceivers' sensitivity to the sticks' suitability for power and precision tasks.

EXPERIMENT 2

Experiment 1 demonstrated that participants were able to perceive a hockey stick's functionality by virtue of wielding the stick, without actually using the stick for the intended tasks and despite the fact that all but one participant were unfamiliar with hockey sticks and lacked hockey playing experience. However, it is possible that experience using the sticks for power and precision tasks could serve to fine-tune participants' responses (cf. Wagman & Carello, 2001). That is, their perceptual experience could be enriched by the opportunity to perform an action with the sticks, and thus could lead to a different pattern of postaction responding when compared to preaction ratings. Using the sticks for power and precision actions could help participants identify the best mass distribution for the tasks, leading, perhaps to a more pronounced preference for the bottom- and top-weighted sticks for those respective tasks. Therefore, we expected stronger effects of mass distribution following the action phases for power and precision tasks.

Method

Participants. Nine undergraduate men and 11 undergraduate women at the University of Cincinnati participated in this experiment in exchange for course credit. Their ages ranged between 18 and 32 years ($M = 19.0$ yrs; $SD = 3.1$ yrs). They averaged 172.7 cm tall ($SD = 11.1$ cm). None had any hockey playing experience.

Apparatus. The same sticks as in Experiment 1 were used. For the power action tasks, participants used the sticks to strike a street hockey puck (111.9 g, 7.6

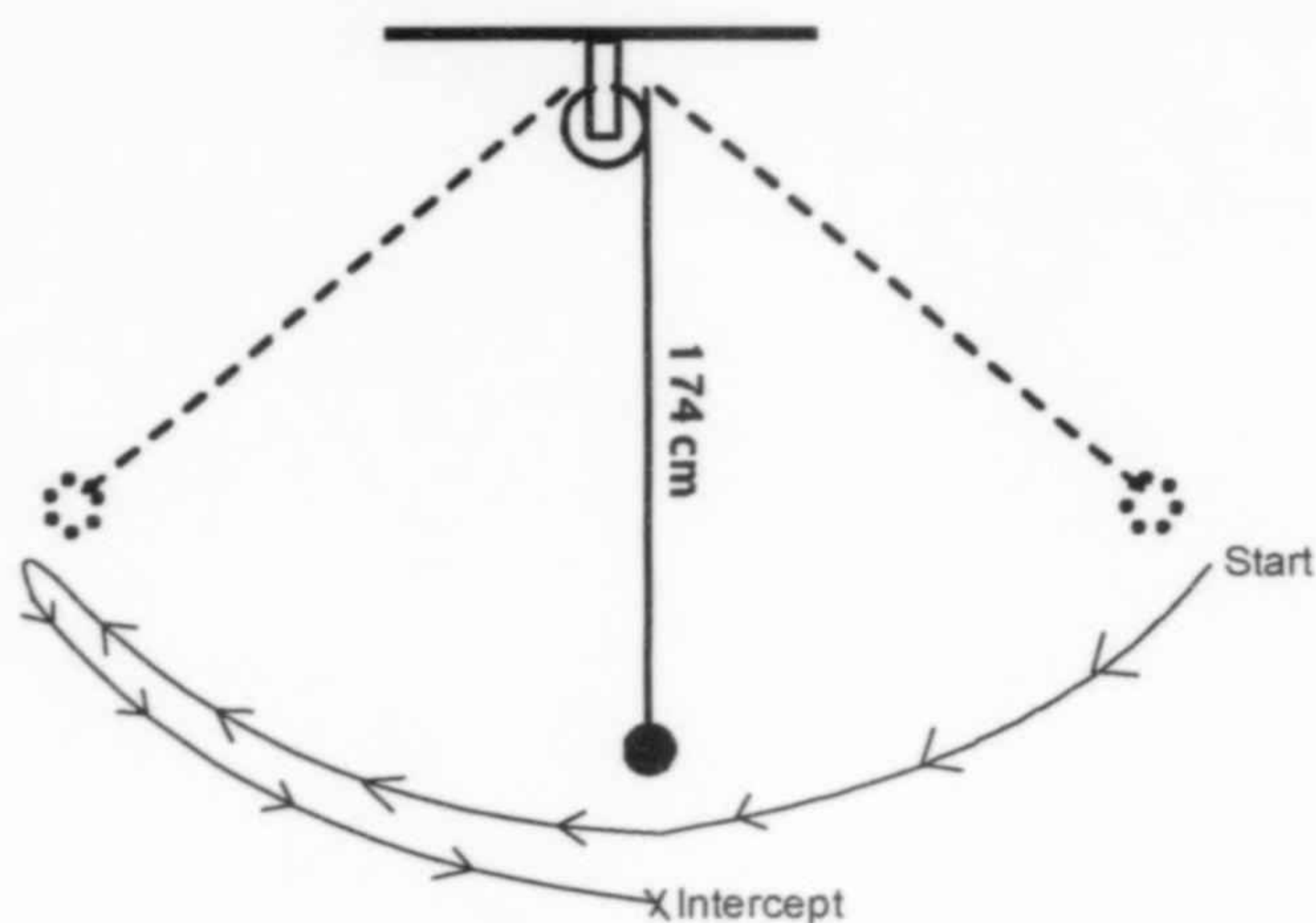


FIGURE 2 The swinging pendulum used in the precision-action phase of Experiments 2-4. The top of the pendulum was attached to the laboratory ceiling. The path length of the trajectory from start to intercept point was approximately 342 cm.

cm diameter $\times$ 2.5 cm tall) into a block of foam padding (142 cm wide $\times$ 181 cm tall). The foam pad was located approximately 125 cm in front of the puck and served to absorb the puck's impact after a shot. For the precision action tasks, participants had to intercept an object attached to a pendulum. The pendulum consisted of a pulley wheel that was fixed to a small board and bolted to the laboratory ceiling. The swinging arm of the pendulum was a rigid wood dowel (174 cm long) that was attached to the center groove of the pulley wheel and adjusted in length to hang 73 cm from the ground when at its vertical hanging position. A small rubber ball (4 cm in diameter) was attached to the end of the dowel and constituted the target to be intercepted with the center of the blade of the hockey stick. Figure 2 depicts the pendulum and its trajectory.

Procedure. Participants in Experiment 2 engaged in three separate phases for both the power and precision conditions. Those experiment phases were preaction ratings, the action phase, and postaction ratings. Participants performed all three phases consecutively for a given perceptual rating task. In the pre- and postaction phases participants performed the same rating tasks, using the same scale, as in Experiment 1. Because the additional experiment phases substantially lengthened the experiment duration, only two trials per condition (total of 12 rating trials: 3 sticks $\times$ two tasks) were conducted.

The action phases intervened between the pre- and postaction rating phases. No performance or rating data were collected during the action phase trials: The only purpose of the trials was to give participants experience using the hockey sticks to perform actions relevant to the rating tasks. Because the action phases required visual guidance, participants completed them with the eyes open. Condition order (power vs. precision task) was blocked across participants so that half of the participants started with the power condition, and half started with the preci-

sion condition. For the action phase tasks (described following in more detail), participants used each of the sticks to hit a puck (power condition) or intercept the ball swinging on the pendulum (precision condition) five times with each stick. No explicit feedback about task performance was given to the participant, although participants could see the results of their actions and thus had a means of gauging their success using the different sticks for the different tasks. All five repetitions with a given stick were performed in a single block of trials. Stick order was counterbalanced across participants. A total of 30 action phase trials (2 conditions $\times$ 5 repetitions $\times$ 3 sticks) were conducted.

Action phase tasks. The action phase of the power condition involved hitting the street hockey puck with each of the hockey sticks. The participant's task was to hit the puck, which was positioned 96 cm in front of the left foot, into the large foam pad. Foot placement for the hitting task was specified with tape markings on the floor; the left and right feet were spaced 45 cm apart. These dimensions for foot and puck placement represented a comfortable stance for conducting a slap shot based on the stick length and grip position used in the experiment. Participants stood facing in the direction of the puck, oriented so as to hit the puck into the foam pad.

The action phase of the precision condition involved maneuvering a hockey stick to intercept the ball at the end of the swinging pendulum. Although the pendulum-interception task is less representative of hockey tasks such as intercepting a puck sliding across a surface, we chose this interception task because it was possible to achieve a greater amount of control over the trajectory of an object attached to a pendulum than an object sliding across the floor. Participants stood with their feet 30 cm apart while holding one of the three hockey sticks. At the beginning of each trial, the participant rested the hockey stick blade on the floor 70 cm to the right of his or her right foot. A piece of tape on the floor indicated where to rest the blade. Participants faced the pendulum, which followed a path along a perpendicular trajectory 115 cm in front of where the participants stood. The pendulum trajectory started from the right and swung to the left side of the standing participant. At the start of each trial, the experimenter held the pendulum 114 cm from its vertical hanging position before letting it fall and swing. Participants watched the pendulum swing from their right side, pass through its full range of motion (i.e., a half cycle), and reverse direction back toward the participant. Participants were instructed to intercept the ball when the pendulum arm was at its vertical position during the second (return) half-cycle so as to arrest the motion of the ball at that point.

Results

Power task. The means and standard deviations of the ratings in the pre-action phase of the power condition for the top-, middle-, and bottom-weight locations, respectively, were $M = 3.40$, $SD = 1.98$; $M = 5.05$, $SD = 1.30$; and M

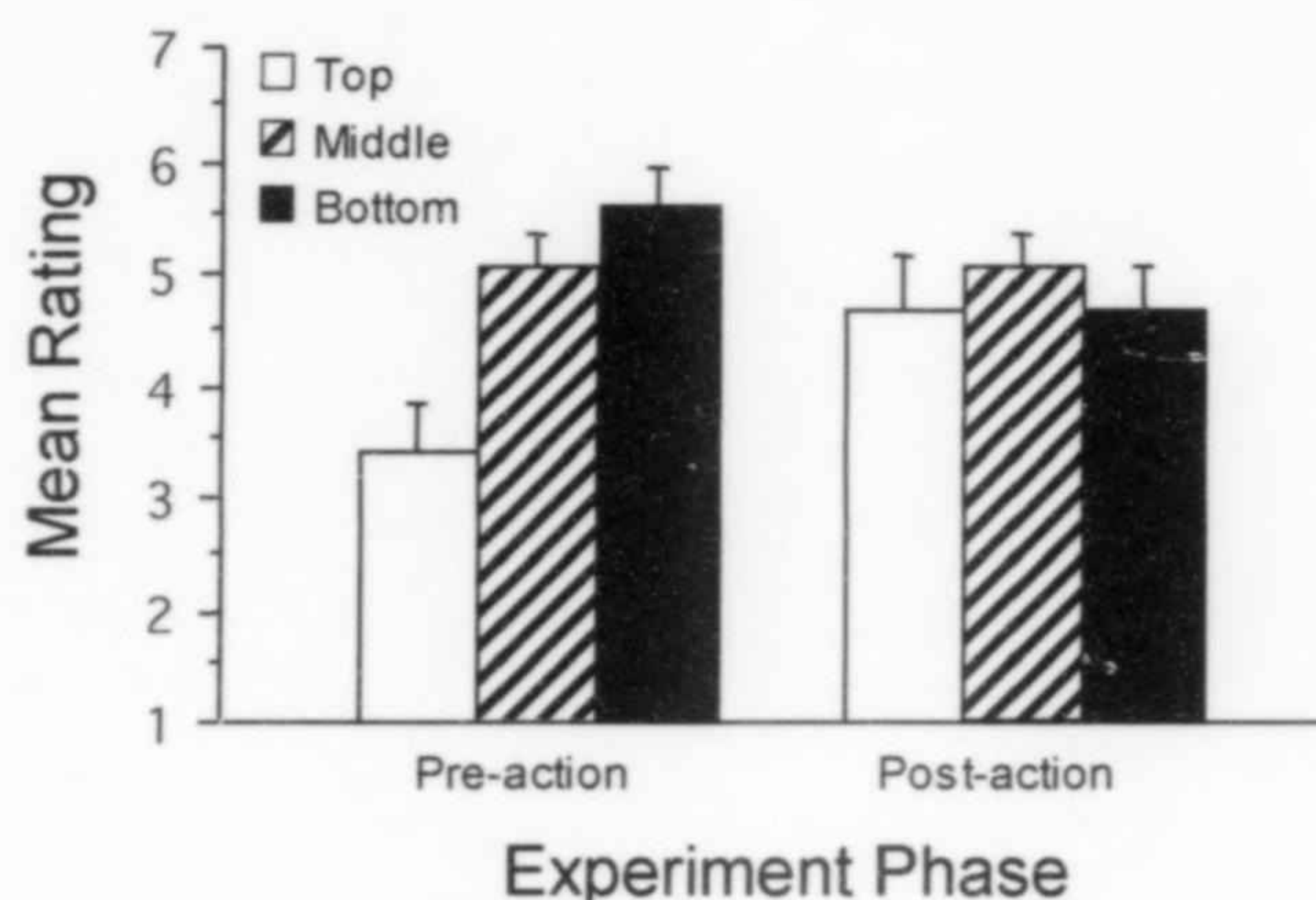


FIGURE 3 Mean hockey stick ratings (error bars indicate 1 standard error) for the power condition in the pre- and postaction phases of Experiment 2.

= 5.58, $SD = 1.51$ (see Figure 3). The postaction ratings for those same respective conditions were $M = 4.68$, $SD = 2.16$; $M = 5.08$, $SD = 1.28$; and $M = 4.65$, $SD = 1.90$. A repeated-measures ANOVA showed that there was a significant interaction between mass location and experiment phase (pre- vs. postaction), $F(2, 38) = 4.80$, $p < .05$, $f = 0.50$. Simple-effects tests indicated that there was a significant main effect of mass location in the preaction phase of the experiment, $F(2, 38) = 8.85$, $p < .001$, but not in the postaction phase, $p > .05$. Bonferroni-Dunn post hoc comparisons performed on the preaction phase data indicated significant differences between the top- and middle-weighted sticks and between the top- and bottom-weighted sticks (both $p < .01$). In sum, the simple-effects analyses indicated that for the preaction phase there was a tendency to prefer the bottom-weighted stick, but the three sticks were rated very similarly to one another in the postaction phase. In addition, there was a significant increase in the rating of the top-weighted stick in the postaction phase, $t(19) = -2.74$, $p < .05$, but no pre-post change in the ratings of the middle- and bottom-weighted sticks, $p > .05$. The primary ANOVA also revealed a significant main effect of mass location, $F(2, 38) = 3.58$, $p < .05$, $f = 0.63$, but the interpretation of that effect must be qualified by the interaction. The main effect of experiment phase was not significant, $p > .05$, $f = 0.25$.

Precision task. The preaction means and standard deviations of the ratings for the top, middle, and bottom mass locations, respectively, were $M = 6.20$, $SD = 0.91$; $M = 3.83$, $SD = 1.65$; and $M = 3.15$, $SD = 1.81$. The postaction ratings for those respective conditions were $M = 5.98$, $SD = 1.14$; $M = 4.05$, $SD = 1.60$; and $M = 3.40$, $SD = 1.85$. The mean ratings are presented in Figure 4. A repeated-measures ANOVA indicated a significant main effect of mass location, $F(2, 38) = 30.11$, $p < .001$, $f = 1.26$, but no significant main effect of experiment

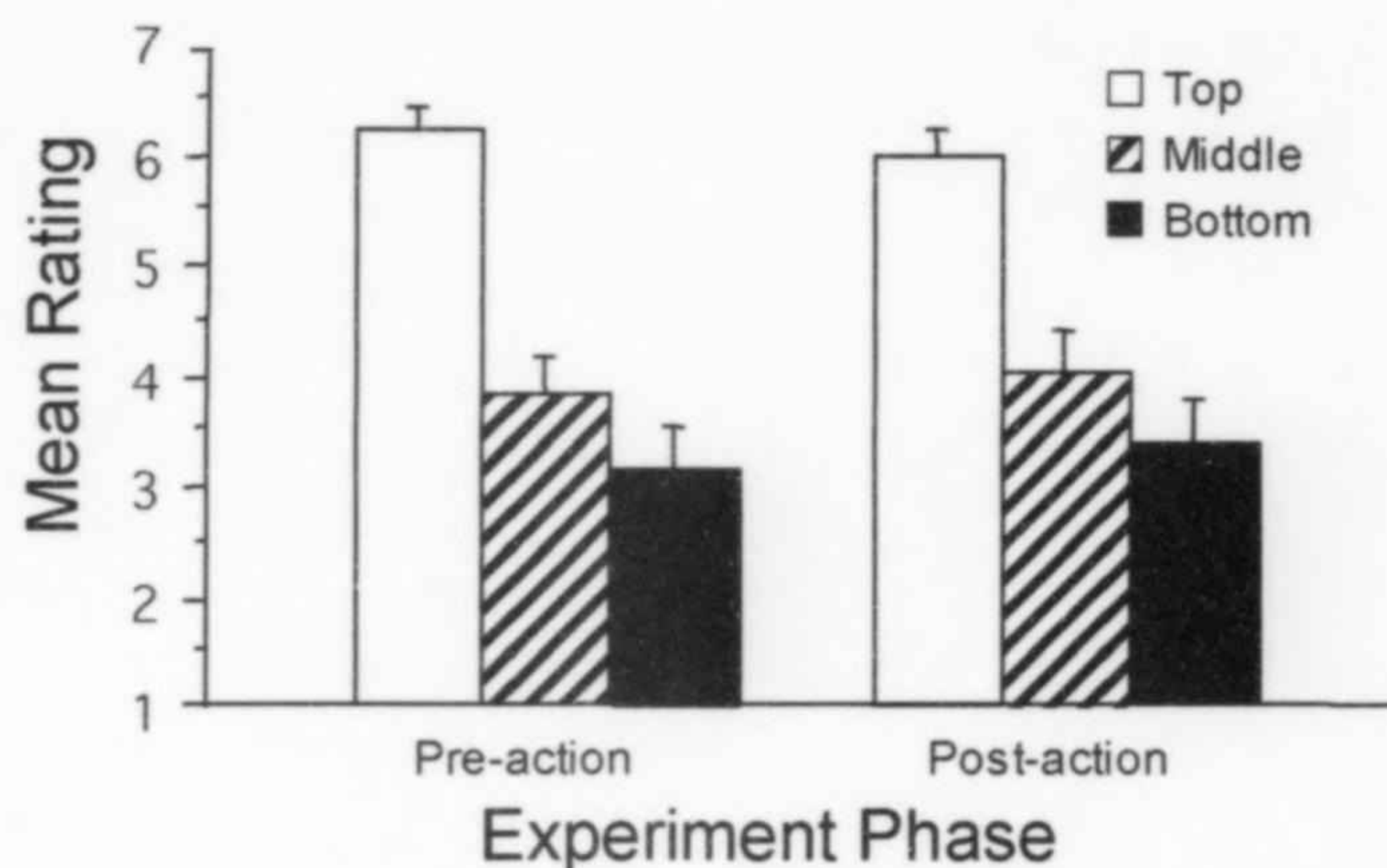


FIGURE 4 Mean hockey stick ratings (error bars indicate 1 standard error) for the precision condition in the pre- and postaction phases of Experiment 2.

phase, $F < 1$, $f = 0.08$, nor an interaction between experiment phase and mass location, $F < 1$, $f = 0.18$. Post hoc Bonferroni-Dunn comparisons indicated significant differences between the top- and middle-weighted sticks and between the top- and bottom-weighted sticks, $ps < .001$. The top-weighted stick was rated higher regardless of experiment phase.

Discussion

Participants provided ratings of the sticks' suitability for power and precision actions before and after performing power and precision tasks. Results for the precision condition were similar across pre- and postaction phases. Participants rated the top-weighted stick most suitable for performing the interception task both before and after they had an opportunity to perform the interceptive action. It was predicted that experience gleaned from actually performing the actions for which participants rated the sticks would enrich participants' perceptions regarding each stick's suitability for performing the precision interception task. Because the pre- and postaction ratings were so similar, it is possible that participants were able to accurately identify the best mass distribution for performing the precision interception action before ever engaging in the behavior, based solely on information obtained from wielding the sticks. The added experience and feedback obtained from the action phase did not significantly affect participants' ratings. The small effect size of experiment phase ($f = 0.08$) and rather modest effect size of the experiment phase $\times$ mass location interaction ($f = 0.18$) observed for precision ratings appear to support our conclusion that added experience did not strongly influence participants' ratings.

The preaction ratings for the power condition in Experiment 2 and the ratings obtained in Experiment 1 were consistent with each other (although the effect size

for mass location was smaller in Experiment 2)—participants tended to prefer the bottom-weighted stick when making judgments about suitability for forcefully striking an object. However, in Experiment 2 the postaction ratings for the power condition differed from the ratings obtained before participants had the opportunity to perform the power task. In the preaction phase (and in Experiment 1) participants preferred the bottom-weighted stick, but in the postaction phase of Experiment 2 participants no longer exhibited a preference for any stick. Moreover, ratings of the top-weighted stick for the power task were significantly higher in the postaction phase than in the preaction phase. These results were unexpected; we anticipated that any preference for the bottom-weighted stick would be amplified in the postaction phase because the bottom-weighted stick was physically optimal for exerting force via striking.

A possible explanation for that unanticipated finding is that participants may have found that making contact with the small puck (7.6 cm diameter $\times$ 2.5 cm tall) required a considerable degree of aiming or precision control over the stick's movement—the power-hitting task may have required an unexpected degree of precision control for accurate task performance, despite the experimenter's instructions to evaluate the effectiveness of each stick for transferring force. To hit a puck with maximal force, the actor must first be able to aim and maneuver the stick to make contact with the puck. The experimenter's observations confirmed that participants experienced some difficulty hitting the puck (e.g., some participants had to swing more than once to make contact on a given trial, and some participants hit the ground with the stick before making contact with the puck). After performing the puck-hitting task, participants may have produced different postaction ratings in response to precision constraints of the hitting task. Experiment 3 was designed to determine whether the unexpected pattern of responding in the postaction phase in the power condition was attributable to the precision requirements of hitting a hockey puck.

Although the direction of change in the postaction ratings for the power task was not anticipated, the results clearly demonstrated that participants' perceptions were affected by the action phase of the experiment. This result is in contrast to the findings of Wagman and Carello (2001), who did not find any strong effects of performing hammering and poking tasks on participants' ratings of differently weighted rods. The opportunity to engage in task-specific perception-action was sufficient to influence perceptions of the hockey sticks' affordances.

EXPERIMENT 3

In Experiment 3 the puck was replaced with a large inflatable ball of sufficient size (21.6 cm diameter; 105.4 g) to have eliminated most of the precision aiming required to make contact with the blade of the hockey stick. We expected, as a result, that participants would rate the bottom-weighted stick as being most favorable for

transferring power to the ball. We expected to replicate the results of Experiment 2 in the precision condition.

Method

Participants. Nine men and six women between the ages of 18 and 40 years participated in this experiment ($M = 21.0$ yrs; $SD = 5.5$ yrs). Participants averaged 174.6 cm tall ($SD = 8.6$ cm). Participants were University of Cincinnati undergraduates who received course credit. None had hockey playing experience.

Apparatus. A rubber ball (21.6 cm diameter; 105.4 g) was used during the power task in place of the puck used in Experiment 2. All other materials were identical to those used in Experiment 2.

Procedure. The procedure was identical to that of Experiment 2, with the exception that instead of making contact with a hockey puck, participants hit the rubber ball during the power-condition action phase.

Results

Power task. The means and standard deviations of ratings for the top, middle, and bottom mass locations were, respectively, $M = 3.90$, $SD = 1.86$; $M = 5.20$, $SD = 1.15$; and $M = 5.33$, $SD = 1.32$; in the preaction phase; and, respectively, $M = 3.73$, $SD = 1.77$; $M = 5.00$, $SD = 1.45$; and $M = 5.27$, $SD = 1.41$ in the postaction phase (see Figure 5). There was a significant main effect of mass location according to a repeated-measures ANOVA, $F(2, 28) = 5.07$, $p < .05$, $f = 0.60$, but there was no significant effect of experiment phase, $F < 1$, $f = 0.16$, nor

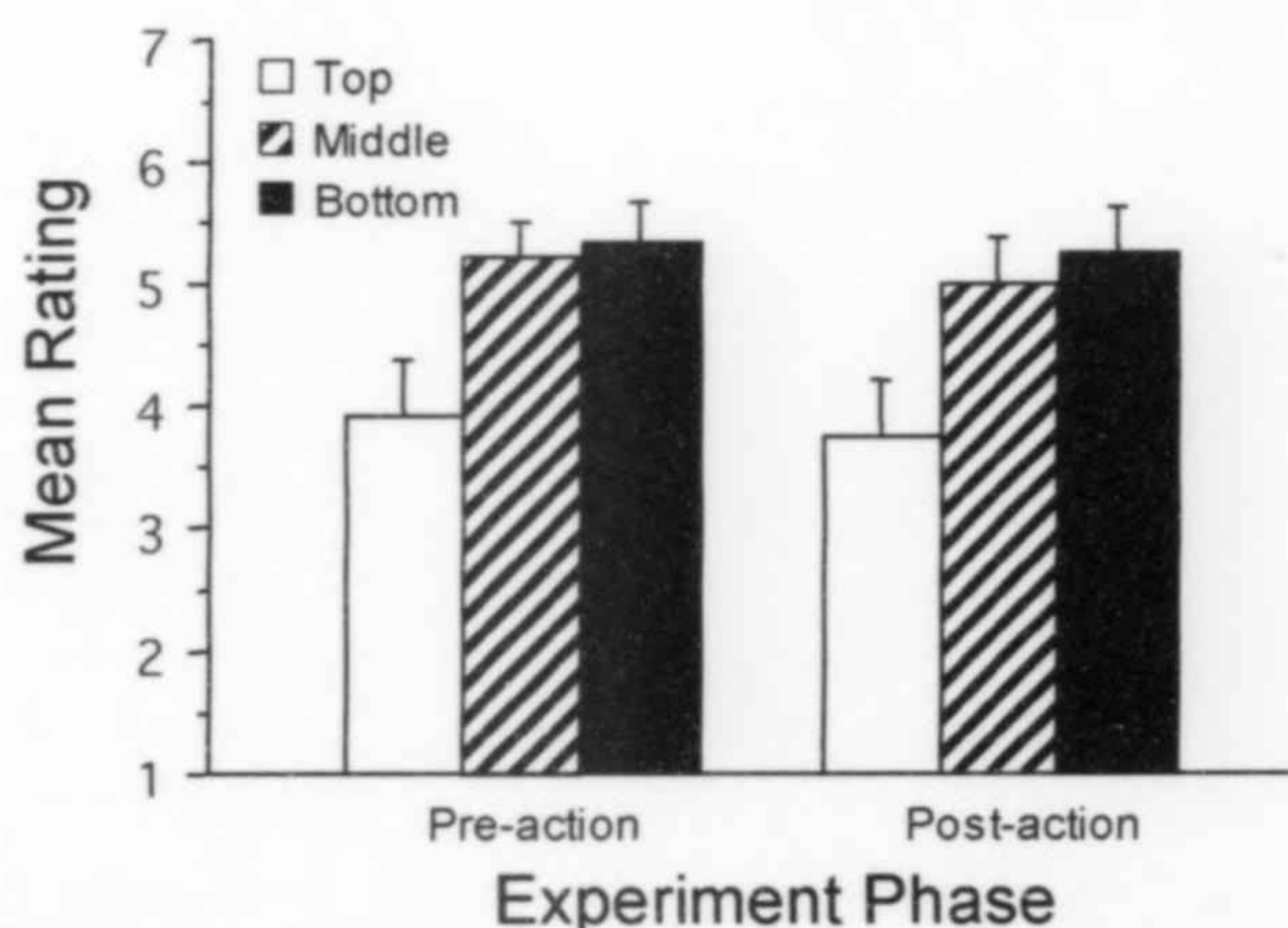


FIGURE 5 Mean hockey stick ratings (error bars indicate 1 standard error) for the power condition in the pre- and postaction phases of Experiment 3.

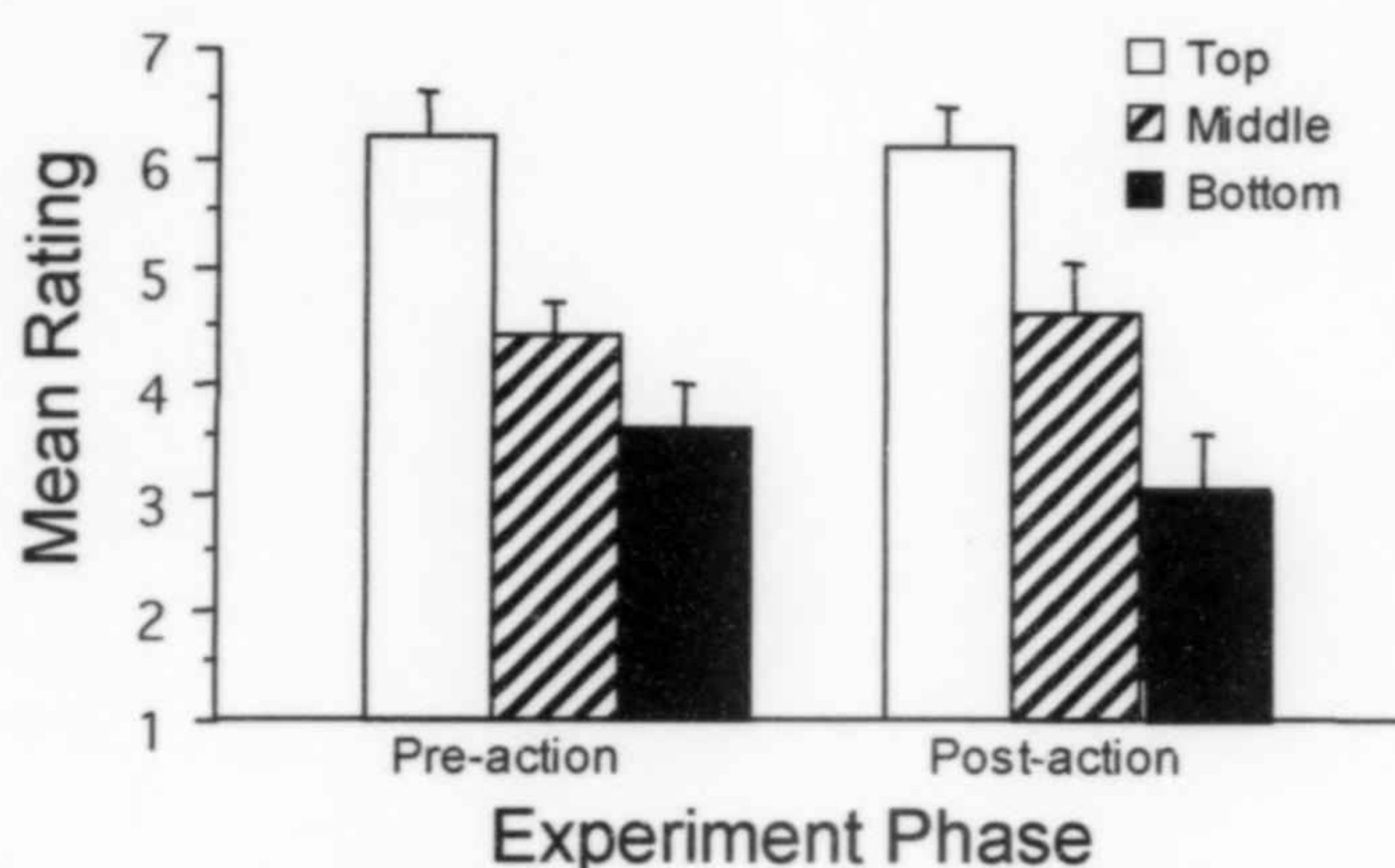


FIGURE 6 Mean hockey stick ratings (error bars indicate 1 standard error) for the precision condition in the pre- and postaction phases of Experiment 3.

an interaction between phase and mass position, $F < 1$, $f = 0.06$. The mean ratings for the top- and bottom-weighted sticks differed significantly according to Bonferroni-Dunn post hoc tests, $p < .01$.

Precision task. The means and standard deviations of ratings for the top, middle, and bottom mass locations were $M = 6.17$, $SD = 1.52$; $M = 4.43$, $SD = 1.02$; and $M = 3.60$, $SD = 1.55$; respectively, in the preaction phase and $M = 6.10$, $SD = 1.31$; $M = 4.63$, $SD = 1.59$; and $M = 3.07$, $SD = 1.80$; respectively, in the postaction phase (see Figure 6). A repeated-measures ANOVA indicated a significant main effect of mass location, $F(2, 28) = 23.26$, $p < .001$, $f = 1.29$, but no significant effect of experiment phase, $F < 1$, $f = 0.20$, nor an interaction between phase and mass position, $F < 1$, $f = 0.18$. Bonferroni-Dunn post hoc tests indicated that all pair-wise comparisons were significantly different, all $ps < .001$.

Discussion

The results of the precision condition essentially replicated the results of Experiment 2. As predicted, in the power condition, participants rated the bottom-weighted stick highest both before and after hitting the ball with the sticks. That result stands in contrast to the postaction ratings obtained in Experiment 2, consistent with the suggestion that hitting a puck does involve a degree of precision to which participants become sensitive after attempting to hit the puck. The pattern of ratings in Experiment 3 indicated that participants were able to accurately identify which mass distribution would function best for transferring force to the ball before actually using the hockey sticks to perform this action, and, once given the opportunity to use the sticks for the power action, participants' initial patterns of responding did not change significantly.

The finding that participants with no hockey playing experience responded differently depending on the size of the object they were asked to strike and on the opportunity to perform the power-hitting task suggests that amount of hockey playing experience may be an important determinant of the perceived utility of differently weighted hockey sticks for power and precision tasks. The results obtained from inexperienced participants in Experiment 2 suggested that their initial perceptions regarding which stick was best suited for transferring power changed once the participants apparently discovered the difficulty associated with hitting the small puck. To address the role of hockey playing experience on ratings of the sticks' suitability for power and precision tasks, Experiment 4 examined ratings obtained from an expert group of collegiate hockey players.

EXPERIMENT 4

The results of the first three experiments showed that participants with no hockey experience are sensitive to the way that a hockey stick's mass distribution determines the stick's suitability for different actions. The results highlight the ability of the haptic perceptual system to inform the perceiver about how a held object can be used (cf. Turvey & Carello, 1995). In the power condition of Experiment 2, participants gave different ratings of the sticks in the postaction phase relative to the preaction phase. The change in ratings in Experiment 2 seems to reflect the participants' inexperience with hitting pucks, which are quite small. The results of Experiment 3, in which participants struck the large ball during the action phase, are consistent with the interpretation that in Experiment 2 experience hitting the small puck led participants to acknowledge a precision requirement for the puck-hitting task.

Another, more direct, way to address the effect of experience level on perceiving affordances of hockey sticks for power and precision tasks is to obtain ratings from a group of expert hockey players. If experience hitting pucks plays a role in judging a stick's effectiveness for a power shot, experts' preaction ratings should reflect attunement to precision demands of hitting pucks. Experiment 4a was designed to address that issue. Members of the men's varsity ice hockey team at Miami University (Oxford, Ohio) served as the group of expert hockey players. They were exposed to the same experimental conditions as in Experiment 2. It was expected that in the power condition, the hockey players would prefer the top-weighted stick, followed linearly by the middle- and then bottom-weighted sticks for both pre- and postaction ratings. To rule out the possibility that the changes in student population and experiment location were responsible for any unique findings in Experiment 4a, a replication of that experiment using Miami University undergraduates with no hockey experience was conducted in Experiment 4b. Results of Experiment 4b were expected to mirror those of Experiment 2 because undergraduates at the University of Cincinnati and Miami University were not expected to respond differently from one another.

Method

Participants. Four men between the ages of 20 and 21 years participated in Experiment 4a ($M = 20.8$ yrs; $SD = 0.5$ yrs). They averaged 179.7 cm tall ($SD = 2.4$ cm). Participants were members of the Miami University Redhawks varsity men's NCAA Division I ice hockey team, which was ranked in the top 10 nationally during the 2003–2004 season. Participants averaged 17 years of experience playing hockey. They were compensated \$15 for their participation. In Experiment 4b, nine men and two women between the ages of 18 and 20 years participated ($M = 19$ yrs; $SD = 0.6$ years). They averaged 179 cm tall ($SD = 9$ cm). All were undergraduate students at Miami University with no hockey experience and received course credit in exchange for their participation.

Procedure. For Experiment 4, the same experimental procedure as in Experiment 2 was employed, with the exception that these experiments were conducted in a laboratory in the Department of Psychology at Miami University. The pendulum apparatus used in Experiments 1 through 3 was transported to and reassembled in that laboratory. In addition, after Experiment 4a was completed, the experimenter asked the hockey players to identify the physical attributes of an ideal hockey stick and to describe the characteristics of the stick that they favored for use in games.

Results

Power task. In Experiment 4a (expert participants) the means and standard deviations of the preaction ratings for the top, middle, and bottom mass locations were, respectively, $M = 5.25$, $SD = 1.71$; $M = 3.75$, $SD = 1.50$; and $M = 2.88$, $SD = 1.44$; and the means and standard deviations for postaction ratings in those respective conditions were $M = 6.00$, $SD = 1.41$; $M = 4.25$, $SD = 0.65$; and $M = 3.13$, $SD = 0.85$ (see Figure 7). That pattern of results was different from the results obtained

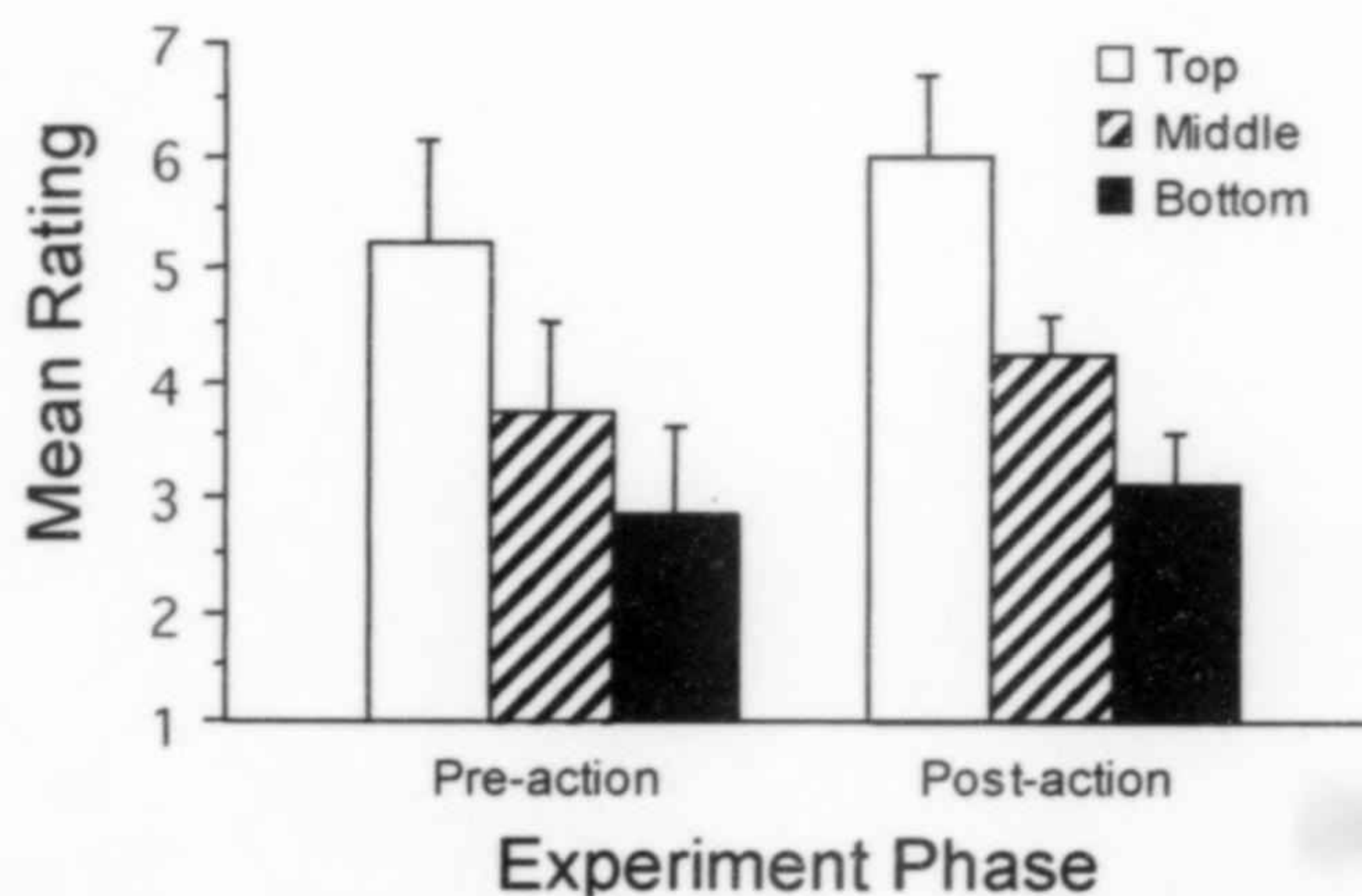


FIGURE 7 Mean hockey stick ratings (error bars indicate 1 standard error) for the power condition in the pre- and postaction phases of Experiment 4a (expert hockey players).

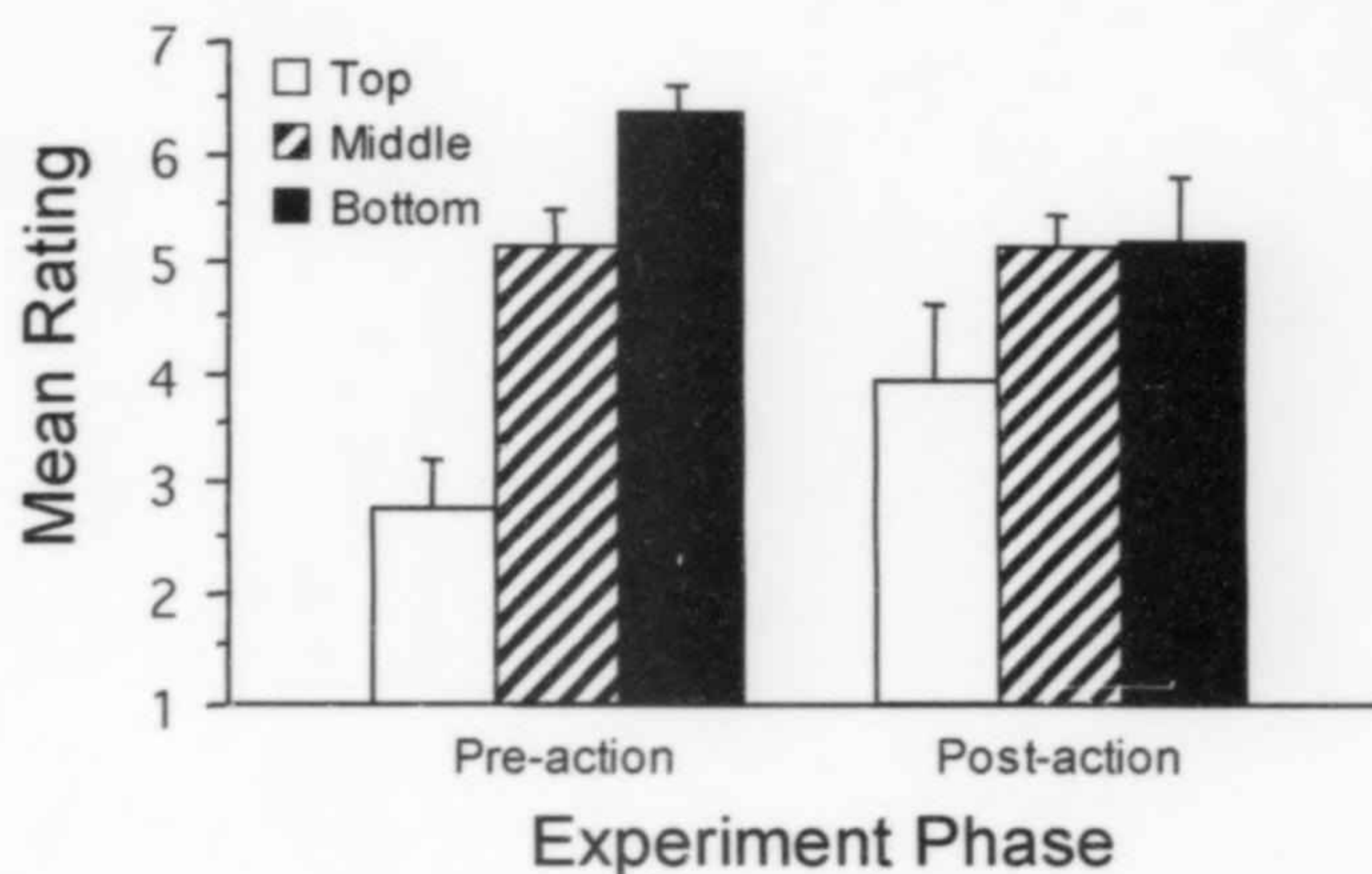


FIGURE 8 Mean hockey stick ratings (error bars indicate 1 standard error) for the power condition in the pre- and postaction phases of Experiment 4b (novice participants).

from the novice participants in Experiment 2. A repeated-measures ANOVA revealed a significant main effect of mass location, $F(2, 6) = 8.15, p < .05, f = 1.65$, but no significant effect of experiment phase, $F < 1, f = 1.28$, nor a significant interaction between phase and mass position, $F < 1, f = 0.13$. Bonferonni-Dunn comparisons revealed significant differences between the top and bottom locations, $p < .01$.

In Experiment 4b (novice participants) the means and standard deviations of the preaction ratings for the top, middle, and bottom mass locations, respectively, were $M = 2.77, SD = 1.46$; $M = 5.14, SD = 1.23$; and $M = 6.36, SD = 0.78$; means and standard deviations of the postaction ratings were $M = 3.96, SD = 2.20$; $M = 5.14, SD = 1.05$; and $M = 5.18, SD = 1.94$ (see Figure 8). A repeated-measures ANOVA revealed a main effect of mass location, $F(2, 20) = 9.11, p < .01, f = 0.95$. The experiment phase main effect was not significant, $F < 1, f = 0$, but there was a significant interaction between mass location and experiment phase, $F(2, 20) = 4.81, p < .05, f = 0.69$. A follow-up ANOVA on the preaction ratings revealed a significant effect of mass location, $F(2, 20) = 25.83, p < .001$. Bonferonni-Dunn comparisons showed significant preaction differences between the top and middle and between the top and bottom mass locations, $ps < .001$. A follow-up ANOVA for the postaction phase did not reveal a significant effect of mass location, $p > .05$. These analyses indicate that the effect of mass location was limited to the preaction phase. Paired t tests comparing each stick across the pre- and postaction phases for the power condition indicated that the bottom-weighted stick was rated significantly lower in the post- than in the preaction phase, $t(10) = 2.80, p < .05$. The decrease in the rating of the top-weighted stick was not significant, and there was no change in the mean ratings of the middle-weighted stick.

Precision task. In Experiment 4a (expert participants) the means and standard deviations of the preaction ratings for the top, middle, and bottom mass locations were, respectively, $M = 6.38, SD = 0.63$; $M = 3.75, SD = 1.26$; and $M = 2.50$,

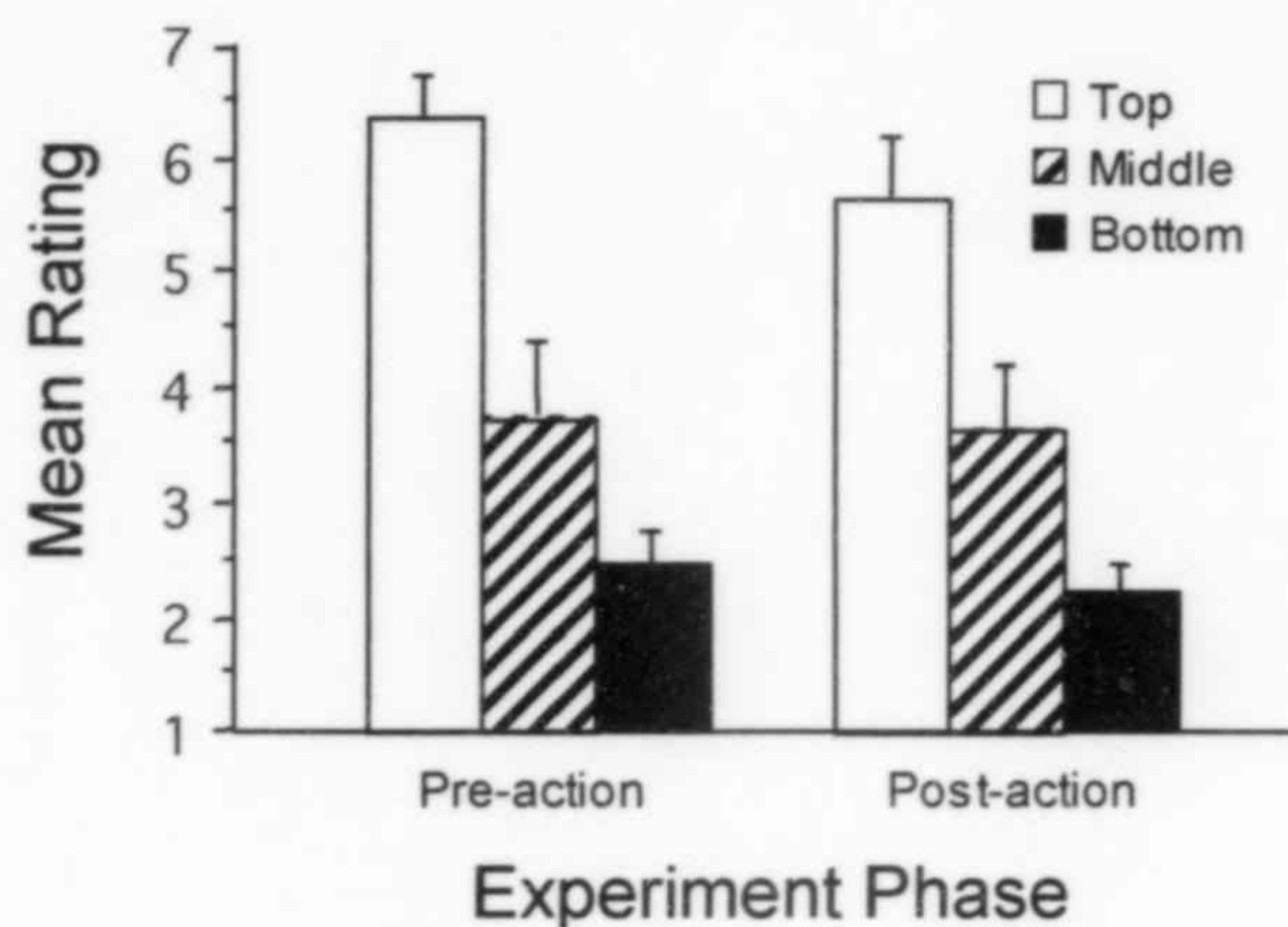


FIGURE 9 Mean hockey stick ratings (error bars indicate 1 standard error) for the precision condition in the pre- and postaction phases of Experiment 4a (expert hockey players).

$SD = 0.58$; means and standard deviations of the postaction ratings in those respective conditions were $M = 5.63$, $SD = 1.11$; $M = 3.63$, $SD = 1.11$; $M = 2.25$, $SD = 0.50$ (see Figure 9). Consistent with the previous two experiments, repeated-measures ANOVA showed a statistically significant main effect of mass location, $F(2, 6) = 24.80$, $p < .001$, $f = 2.87$, but no effect for experimental phase, $f = 0.81$, nor an interaction, $F < 1$, $f = 0.49$. Bonferroni-Dunn comparisons revealed significant differences between the top and middle locations and between the top and bottom locations, $ps < .01$.

In Experiment 4b (novice participants) the means and standard deviations of the ratings for the top, middle, and bottom mass locations, respectively, were $M = 6.36$, $SD = 1.00$; $M = 3.82$, $SD = 1.40$; and $M = 2.86$, $SD = 0.81$; for the preaction phase,

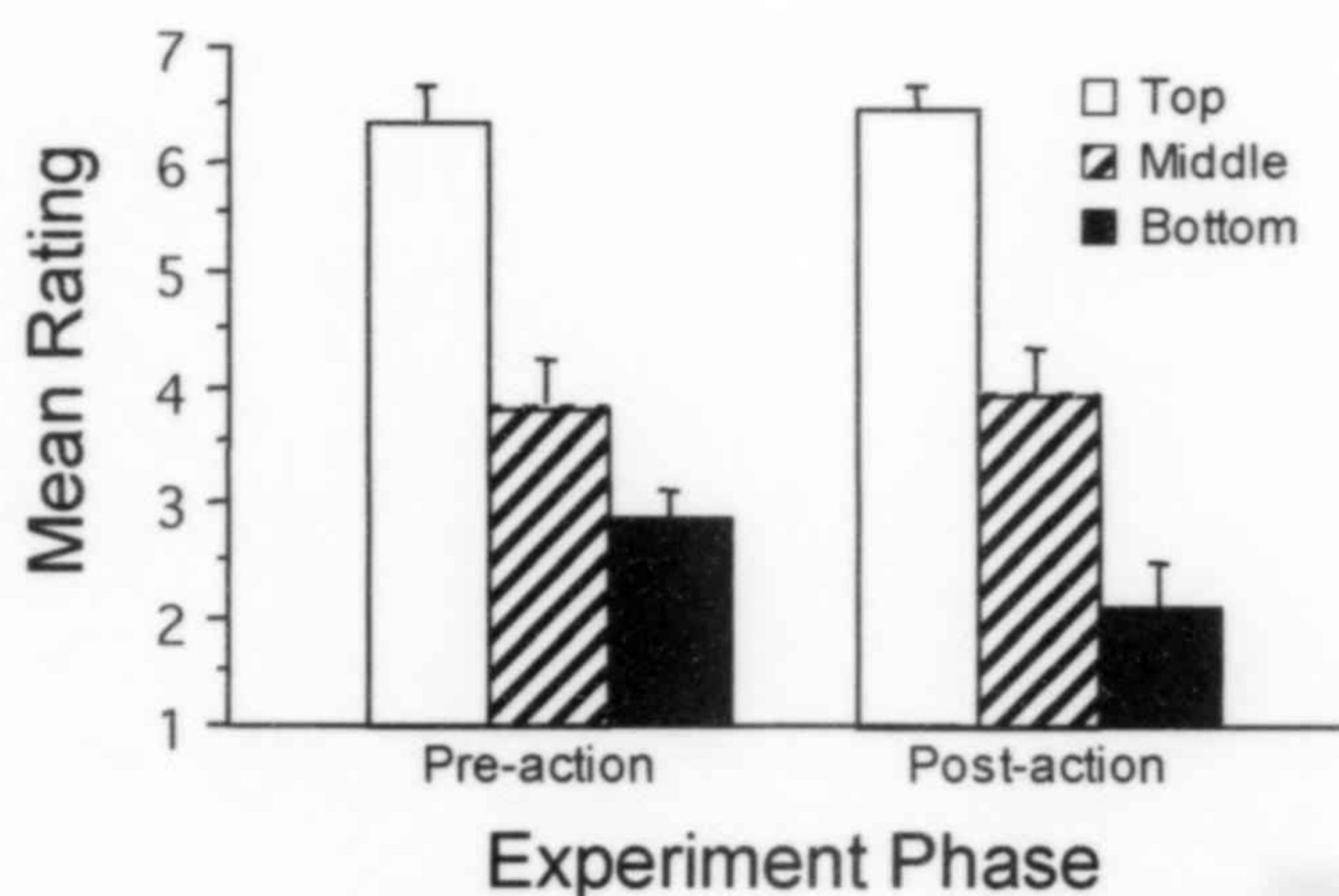


FIGURE 10 Mean hockey stick ratings (error bars indicate 1 standard error) for the precision condition in the pre- and postaction phases of Experiment 4b (novice participants).

and $M = 6.46$, $SD = 0.69$; $M = 3.96$, $SD = 1.29$; and $M = 2.09$, $SD = 1.24$; for the postaction phase (see Figure 10). A repeated-measures ANOVA revealed a significant main effect of mass location, $F(2, 20) = 105.38$, $p < .001$, $f = 3.25$. All possible Bonferonni-Dunn pair-wise comparisons were significant, $p < .001$. The interaction between experimental phase and mass position was not significant, $f = 0.49$, nor was there a main effect of phase, $f = 0.44$.

Discussion

Experiment 4b, a replication of Experiment 2 using Miami University undergraduates, yielded results similar to those of Experiment 2. These results rule out the possibility that the pattern of responses obtained from the expert hockey players in Experiment 4a were an artifact of collecting data at a different location.

In Experiment 4a, the expert hockey players preferred the top-weighted stick, followed by the middle- and then bottom-weighted sticks, for both pre- and postaction ratings in both the power and precision conditions. The ratings were consistent across participants and their ratings were apparently uninfluenced by performing the action task. Although the relatively large effect size of experiment phase ($f = 1.28$ and 0.81 for the power and precision tasks, respectively) indicated that the nonsignificant results must be treated with caution, trends in the data do not compromise our interpretation of the results because there was no evidence that participants changed their ratings differentially across sticks after performing the action-phase tasks. For the power condition there was a trend to rate all of the sticks higher after performing the power task, and for the precision condition there was a trend to rate the sticks lower after performing the interception task.

The hockey players' precision condition ratings were consistent with the ratings offered by novices in the previous experiments and in Experiment 4b. Their power condition ratings differed in important ways, however. In the preaction phase for the power task, the hockey players seemed to have been influenced by how the stick's mass distribution would function for hitting a puck, rather than considering more abstractly which mass distribution would yield a maximal transfer of force to a struck object in the absence of a precision requirement. Although there were trends (associated with large effect sizes) for the hockey players to change their power and precision ratings after performing the action-phase tasks, the important difference between this experiment and Experiment 2 is not the nonsignificant experiment phase effect or Mass Location $\times$ Experiment Phase interaction, but the finding that in the preaction phase the hockey players rated the top-weighted sticks higher than the bottom weighted sticks.

The hockey players' reasons for preferring the top-weighted mass distribution became apparent once they were asked to clarify their opinion of what makes for an ideal hockey stick. They all described their preference for a "light" stick, stating their primary consideration was in terms of being able to control or "stick handle" the puck. The hockey players furthermore reported that, all other factors being

equal, the flex of the stick shaft is more important in determining their perceptions of a stick's suitability for maximally transferring force to a puck than the absolute "bottom-heaviness" of the stick. Future investigations along the lines of this study should manipulate shaft flexibility because the experts' judgments of a stick's suitability for power seem to depend on factors other than (or at least in addition to) mass distribution. It seems that the question of which variables matter may depend on the level of hockey expertise of the perceiver—different expertise levels may determine the relative importance of different physical properties of the hockey sticks. A tool's performance could be relatively unaffected by a particular physical parameter of the tool if the tool user does not possess the skill or knowledge to exploit the variable to maximize the benefit of the tool. Expertise, considered as contributing to the action capabilities of the actor, could thus contribute to determining the affordances of an object. This hypothesis could hold true in a variety of tool-use settings, and warrants additional research. The power condition results in response to the manipulation of mass distribution nevertheless indicated that expert hockey players are sensitive to the precision constraints involved in hitting pucks for maximal power.

Perception of a held object's weight has been shown to be tied to the object's mass distribution (i.e., inertia), rather than simply to the object's mass, *per se* (e.g., Shockley, Carello, & Turvey, 2004; Shockley, Grocki, Carello, & Turvey, 2001; Turvey et al., 1999). Because the top-weighted stick had the lowest moment of inertia of the three sticks, it may have felt lighter. To address the concern that the hockey players may have been biased toward preferring, above all else, lighter sticks, they were asked to perform one additional perceptual task after they had participated in all experimental trials. The players were asked to close their eyes and were subsequently given each of the three sticks to wield. The experimenter asked them to rank order the sticks in terms of suitability for pounding a peg into the ground—they were asked to consider the sticks' functionality for a power task in a context completely removed from the game of hockey. All four participants ranked the bottom-weighted stick as being most suitable to the hammering task, followed by the middle- and then the top-weighted sticks. Those results, although gathered in a somewhat informal manner, suggested that their ratings for the power condition reflected hockey-specific task demands, rather than an outright bias for lightweight sticks or an inability to determine which stick was best suited for absolute force transfer.

GENERAL DISCUSSION

The results of these experiments support the notion that people can use the haptic perceptual subsystem of dynamic touch to perceive how a held object may be used (i.e., its affordances; see also Bongers, Smitsman, & Michaels, 2003; Carello, 2004; Dainoff & Wagman, 2004; Shockley et al., 2004; Shockley et al., 2001; Wagman & Carello, 2001, 2003; Wagman & Taylor, 2004). The results moreover indicated

that it is possible to coordinate the two hands to function as a unitary perception-action device, responsible for both producing the exploratory wielding actions and registering the information about the hockey sticks' affordances. Experiment 1 suggested that variations in mass distribution sufficiently differentiated hockey sticks in terms of their perceived functionality. Experiment 2 sought to determine whether engaging in an action task might further constrain perception of which mass configuration might function best for power and precision actions. Participants were influenced by performing the power task, but not in the manner that was anticipated. Preaction ratings in Experiment 2 indicated that participants felt the bottom-weighted stick would, as expected, function best for the power task. However, after having performed the task those participants apparently realized that contact with the puck required a considerable degree of precise control and aiming of the stick—they seem to have discovered that to transfer maximum power to the puck it was first necessary to precisely aim the stick to contact the small puck, a task most easily accomplished using the top-weighted stick.

That unanticipated result guided the design of Experiment 3, which was an attempt to resolve the shift in how participants responded in the postaction phase for the power task. A large inflatable ball replaced the puck used in Experiment 2. The larger surface area of the ball vastly reduced precision aiming requirements and resulted in a true power-transferring task. The results of Experiment 3 were consistent with the hypothesis that the small size of the puck was responsible for the unexpected postaction ratings in Experiment 2. In Experiment 3, participants preferred the bottom-weighted stick for transferring force during both the pre- and postaction phases. Experiment 4a employed varsity-level hockey players as participants to evaluate the role of hockey playing experience. The hockey players preferred the top-weighted mass distribution for both tasks during both pre- and postaction phases.

It could be argued that participants in our experiment were not perceiving affordances of the sticks, *per se*, but rather were mapping variations of mass distribution onto the two response categories because they assumed there was an experimenter expectation that would dictate such a mapping. That is, participants may have assumed that variation of mass distribution in one direction was meant to correspond to enhanced suitability for one of the tasks and that variation in the other direction was meant to correspond to enhanced suitability for the other task. Two findings suggest that this was unlikely, however. First, in Experiments 1 and 2, for instance, every participant displayed the same pattern of ratings; no one mapped the variation of mass distribution in the opposite direction (bottom-heavy better for precision and top-heavy better for power tasks), which would seem equally plausible if participants had behaved in a manner suggestive of an expectation effect of some sort. Second, the reversal of power condition results across the pre- and postaction phases in Experiment 2 is inconsistent with that interpretation. It seems instead that participants' responses were based on a more meaningful perceptual experience than arbitrarily mapping the variation in the sticks' mass distribution to the two perceptual categories.

In sum, the results of these experiments highlight three notable characteristics of haptic perception using the subsystem of dynamic touch: (a) Perceivers can, within limits, use dynamic touch to perceive affordances; (b) Perceivers can softly assemble perception-action devices tailored to task demands (Bingham, 1988; Runeson, 1977)—in this case, a bimanual wield-and-detect device; and (c) Haptic sensitivity to action-relevant properties of objects seems to be modifiable with experience. These experiments demonstrated that people are able to judge, with reasonable success, how variations in the mass distribution of hockey sticks would affect their ability to utilize the sticks to perform two different kinds of tasks.

The Role of Experience in Perceiving Affordances by Dynamic Touch

A novel feature of Experiment 4 in comparison to recent work on perceiving affordances of tools by dynamic touch (Wagman & Carello, 2001, 2003; Wagman & Taylor, 2004; but see Carello et al., 1999; Carello et al., 2000) was that we employed expert tool users as participants. The expert hockey players identified the top-weighted stick as being the optimal mass configuration for performing both power and precision actions. Novice participants' preaction ratings for the power puck-hitting condition differed from the players' ratings, but after the novices completed the action phase, their postaction ratings aligned with the hockey players' ratings. The opportunity to explore the relation between the feel of the hockey sticks and the sticks' actual performance when hitting the pucks seems to have allowed the novice participants to discover the emergent behavioral constraints associated with hitting a puck for power, leading them to apparently perceptually "tune in" to the same action constraints that governed the experts' ratings. The nature of the process underlying this adaptive change in performance could be a form of perceptual learning related to perceptual attunement—the process of discovering the information that specifies the affordance (E. J. Gibson & Pick, 2000; J. J. Gibson, 1966)—or an example of calibration of responses to an informational variable (Wagman, Shockley, Riley, & Turvey, 2001; Withagen & Michaels, 2005), or could be due to some other factor that is not identifiable with perceptual learning. Additional research will be required to examine those possibilities.

That result also points to the powerful constraining role played by context and behavioral goals. Under different task constraints—abstractly considering a stick's suitability for power tasks without having used the stick in a specific context versus considering a stick's suitability for transferring force to a specific small object (the puck)—participants gave different ratings for the differently weighted sticks. This result provides empirical support for E. J. Gibson and Pick's (2000) claim that "in a true tool-using operation, the tool has an affordance in relation to the goal, and this relation must be perceived" (p. 99).

Additional Human Factors Implications

Well-designed tools and implements should not only complement the anatomical and biomechanical characteristics of the user, but also the perceptual characteristics of the user. The possibilities for action afforded by the tool or other artifact should be perceptually specified to the user (Warren, 1995). Even though it is recognized that designed artifacts should visually communicate their utility to the user (Norman, 1988; Zaff, 1995), it is less widely recognized that hand-held artifacts such as tools should also haptically communicate their utility. This is an important consideration because perceivers can use dynamic touch (and, presumably, other haptic subsystems) to perceive the affordances of hand-held tools.

Additional research is needed to determine how tool users learn to identify the "feel" that indicates whether an object is appropriate or optimal for a given task. Research along those lines may produce broadly applicable data that could help product designers and human factors specialists develop techniques to facilitate the safe and rapid adoption of new or newly designed products, whether those products are hockey sticks, other sports implements such as golf clubs, or other types of hand-held tools and products. It may, for instance, prove beneficial to manipulate the density of materials of a hockey stick's shaft or to place small weights inside the shaft of the stick to achieve an optimum "maneuverable feel" to the stick, resulting in a hockey stick that capitalizes on the sensitivity of dynamic touch to action-relevant properties of held objects. It may also be useful to produce "novice" and "expert" sticks that differ with respect to their mass distributions.

Ergonomics guidelines from the National Institute for Occupational Safety and Health (2004) and the International Labour Organization (Frazer, 1980) suggest making hand-held tools as light as possible to reduce injury and fatigue associated with their use. Those are certainly desirable goals. However, those guidelines do not include consideration of how a tool's purpose should dictate its distribution of mass, or of how a tool's distribution of mass has perceptual consequences that may in turn affect how the tool is used. Given that the results of this study suggest that tool users are capable of using dynamic touch to perceive affordances (see also Wagman & Carello, 2001, 2003; Wagman & Taylor, 2004), it may be important to design tools that haptically guide their proper use. For instance, a tool designed for precision use should not have its concentration of mass located at a point distal to where the tool is grasped. A person may misuse a tool designed in such a way (e.g., as a hammer), leading to inefficiency or even to injury. If design constraints make it unavoidable to eliminate weight near the distal working point of the tool, adding weight near the handle (in contradiction of ergonomic guidelines to make tools as light as possible) may discourage improper use of the tool and may also serve to improve actual tool controllability. Understanding how the feel of an implement or tool communicates its usability can serve as an important constraint on the design process.

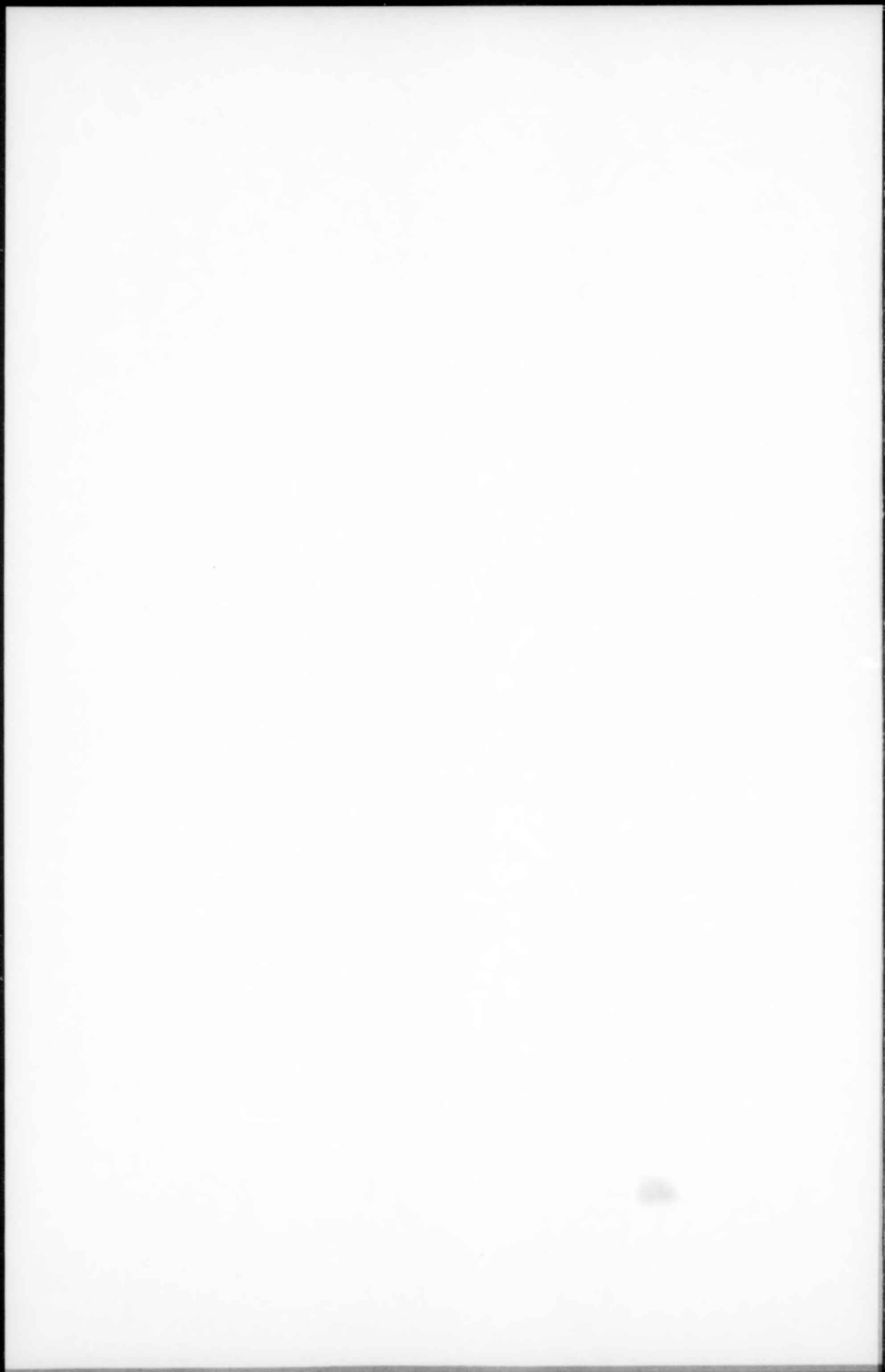
ACKNOWLEDGMENTS

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Postural Stabilization of Visually Guided Eye Movements

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We studied relations between eye movements and postural control. In two experiments, participants were asked to shift gaze to follow horizontal oscillation of visual targets. Postural sway variability was reduced during target oscillation, relative to sway with a stationary target. Target displacement amplitude was within the range that normally does not elicit head rotation, and measured head rotation did not increase during target motion. Eye movements made when the eyes were closed did not yield a reduction in body sway (relative to sway when the closed eyes were stationary). The amplitude and frequency of eye movements matched the amplitude and frequency of target motion. The results undermine the view that eye movements and postural control compete for limited central processing resources, and document a functional integration of postural control with visual performance.

Tasks or behavioral goals that are superordinate to the control of posture may be termed *suprapostural tasks* (Stoffregen, Pagulayan, Bardy, & Hettinger, 2000;

Stoffregen, Smart, Bardy, & Pagulayan, 1999). Suprapostural tasks and postural control are defined and evaluated in qualitatively different terms. For example, reading is not evaluated in terms of the position or motion of the body's center of mass, the minimization of global optical flow, and so on. Body sway can influence performance at some suprapostural tasks (e.g., uncontrolled sway can interfere with reading), but performance of suprapostural tasks is measured in different terms (e.g., reading rate or comprehension). In general, values of postural parameters are not informative about suprapostural task performance. For example, a large excursion of the center of mass might degrade visual performance (e.g., if the person began to fall over), but it could facilitate visual performance (e.g., if the person leaned to bring the eyes closer to a visual target).

It is widely understood that suprapostural activity can influence the control of stance (e.g., Bernstein, 1996; Jeka, 1995; Newell, 1986; Reed, 1988; Slijper & Latash, 2000; Woollacott & Shumway-Cook, 2002). This effect typically is attributed to one of two causes. Many suprapostural activities involve motions of the body or its parts such as occur in reaching, walking, and so on. In such cases, suprapostural activity will influence posture because these suprapostural activities tend to affect the position or motion of the center of mass (e.g., Commissaris & Toussaint, 1997; Friedli, Hallett, & Simon, 1984; Lee, 1980; Slijper & Latash, 2000). Perturbations of the center of mass are thought to have a direct influence on postural control (e.g., Giese, Dijkstra, Schöner, & Gielen, 1996; Nashner & McCollum, 1985).

Posture can be influenced even when suprapostural activity does not perturb the center of mass. Postural control is influenced by tasks, such as visual search, verbal reaction time, and mental arithmetic, that appear to have no mechanical influence on the position or motion of the center of mass (e.g., Dault, Geurts, Mulder, & Duygens, 2001; Hunter & Hoffman, 2001; Kerr, Condon, & McDonald, 1985; Maylor & Wing, 1996; Stoffregen et al., 2000; Stoffregen et al., 1999; Teasdale, Bard, LaRue, & Fleury, 1993). Effects of this kind have often been interpreted in terms of cognitive processes such as the allocation of central processing resources (for a review, see Woollacott & Shumway-Cook, 2002). An alternative interpretation is that posture might be controlled, in part, so as to facilitate performance of suprapostural tasks that make demands on perceptual performance (Riccio & Stoffregen, 1988), such as touching (Riley, Stoffregen, Grocki, & Turvey, 1999) and looking (Stoffregen et al., 2000; Stoffregen et al., 1999). In this study we evaluated the hypothesis that postural control might be modulated adaptively to facilitate changes in the direction of gaze. Our results suggest that postural control actions can be tuned to facilitate the control of changes in the direction of gaze.

In this article we distinguish between saccadic eye movements that are visually guided (i.e., saccades whose success is evaluated in terms of their tendency to maintain or improve the visibility of objects and events in the environment) and those that do not depend on visual guidance (e.g., saccades made in the dark or with the eyes closed). Visually guided eye movements are used to change the direction of gaze or to shift gaze. Gaze shifts can be accomplished by visually guided eye

movements, by visually guided head movements (rotations), or by a combination of these. When the angular change in the direction of gaze is less than 15° , shifts in gaze commonly are achieved without rotation of the head, using only visually guided saccades (Hallet, 1986). In our experiments experimentally induced shifts in gaze were always less than 15° . For this reason, in this article the terms *changes in the direction of gaze*, *shifts in gaze*, and *visually guided eye movements* are equivalent.

CENTRAL COMPETITION OR FUNCTIONAL INTEGRATION?

A substantial literature has grown up around the idea that there may be important relations between the control of posture and the execution of simultaneous suprapostural tasks. In the typical paradigm, experimenters measure body sway while standing participants perform a suprapostural task. Sway under these conditions is compared with sway observed during "quiet stance," that is, without an explicit suprapostural task. Several studies have reported significant increases in body sway during performance of an explicit suprapostural task, such as visual matching (Dault et al., 2001), auditory reaction time (e.g., Lajoie, Teasdale, Bard, & Fleury, 1993), or mental arithmetic (e.g., Maylor & Wing, 1996; Yardley, Gardner, Leadbetter, & Lavie, 1999). Researchers have concentrated on understanding the increase in body sway that sometimes accompanies tasks of this kind. These effects have often been interpreted in terms of the competitive allocation of central processing resources to postural and suprapostural activities (e.g., Lajoie et al., 1993; Teasdale et al., 1993) and more generally, between two tasks being performed simultaneously (e.g., Abernethy, 1988; Navon & Gopher, 1979). The general idea is that postural and suprapostural activities constitute separate tasks, each of which draws on a central pool of cognitive processing resources. This view leads to the general prediction that combination of postural control with suprapostural activity should lead to degradation in performance of postural control, of the suprapostural task, or both.

By contrast, we have argued that postural control can be tuned to support the achievement of suprapostural activities (Riccio & Stoffregen, 1988; Riley, Mitra, Stoffregen, & Turvey, 1997; Riley et al., 1999; Stoffregen et al., 2000; Stoffregen et al., 1999). Our view suggests that, rather than interacting in a competitive manner, posture and certain types of suprapostural activity can be integrated so that their simultaneous performance need not lead to degradation in either and can, in fact, lead to improved performance. In the next section, we review the empirical basis for this view.

Postural Stabilization of Visual Performance

Stoffregen et al. (2000) measured postural sway while standing participants performed one of two visual tasks. One group of participants looked at a blank target

(participants were not asked to maintain fixation on a specific point, and so we refer to this as an inspection task, not a fixation task). A second group of participants looked at a target covered with text, and were asked to search the text, identifying and counting instances of a designated target letter. The manipulation of visual task was crossed with variation in the distance of targets (the visual angle of targets was held constant across variations in distance). The amplitude of postural sway was operationalized in terms of the standard deviation of body position. There was a main effect of suprapostural task on the variability of sway (there was also a main effect of target distance; cf. Stoffregen et al., 1999). As predicted, during visual search, the variability of anterior-posterior (AP) sway was significantly lower than during inspection of the blank targets.

The visual search task used by Stoffregen et al. (2000) required an extended series of coordinated shifts of gaze (visually guided eye movements), alternating with brief periods of stationary gaze (fixation). In contrast, the inspection task was tolerant of reduced precision in the control of shifting and stationary gaze. Functional changes in sway might have been organized to facilitate the control of stationary gaze, of shifting gaze, or both. In this study, we evaluated the hypothesis that body sway can be modulated to support changes in the direction of gaze. Following our earlier research (Riccio & Stoffregen, 1988; Riley et al., 1997; Riley et al., 1999; Stoffregen et al., 2000; Stoffregen et al., 1999), we hypothesized that there would be a functional relationship between body sway and visually guided eye movements. This is because the accuracy of such movements can be influenced by small changes in body sway. By contrast, eye movements that are not visually guided (e.g., eye movements made in the dark, or with eyes closed) are not subject to facilitation or disruption by small changes in body sway.

Eye Movements and Body Sway

The finding that body sway is reduced during a visual search task (Stoffregen et al., 2000) raises the possibility of a functional relation between body sway and eye movements: During visual search, body sway might be modulated to facilitate eye movements that shift gaze. Very little existing research is relevant to this issue. There is a large literature on relations between vision and posture (for partial reviews, see Warren, 1995, 1998), and there is a large literature on eye movements (for a review, see Rayner, 1998), but the overlap between these literatures is small. This is because the majority of studies on eye movements are conducted in the absence of postural sway, using seated participants who are subjected to head restraint (either bite bar or chin rest).¹ This means that studies of eye movements generally have not considered the consequences of body sway. Similarly, studies relating vision to stance generally have not considered eye movements. Some au-

¹For a critique of the study of eye movements in these "unnatural" conditions, see Steinman, Kowler, and Collewyn (1990).

thors have suggested that visually controlled eye movements may be relevant to postural control (e.g., Dault et al., 2001), but very few relevant data have been collected.

Of the few studies that have examined eye movements during unrestrained stance, most are of doubtful relevance to visual guidance of eye movements, due to the inclusion of nonoptical factors such as inertial stimulation of the vestibular system (induced by voluntary head movements; Steinman & Collewyn, 1980; or by imposed motion of the body; e.g., Welch, Bridgeman, Williams, & Semmler, 1998) or muscle vibration (Ivanenko, Grasso, & Lacquaniti, 1999). Skavenski, Hansen, Steinman, and Winterson (1979) studied eye movements and retinal slip during unrestrained quiet stance. They instructed participants to fixate a stationary target at optical infinity. Recordings were made of eye and head position, but there was no measurement of body motion. As noted earlier, the visual search task used by Stoffregen et al. (2000) required shifts in gaze. However, these shifts were not the focus of the study, and there was no controlled manipulation of the direction, frequency, or amplitude of gaze shifts.²

Researchers who have addressed relations between eye movements and body sway have tended to predict that sway should increase during eye movement, relative to sway when the eyes are stationary. There are two motivations for this prediction. One is based on the idea of between-task competition for limited central processing resources (Hunter & Hoffman, 2001; Maylor & Wing, 1996; Teasdale et al., 1993), as discussed earlier. On this view, cognitive resources devoted to the control of eye movements would not be available for the control of stance. Thus, we might expect an increase in body sway when people use eye movements to, for example, track the motion of a visible target.

The second reason that sway might increase during eye movement derives from the concept of saccadic suppression (Oblak, Gregoric, & Gyergyek, 1985; White, Post, & Leibowitz, 1980). A large database suggests that the pickup of information from the optic array is suppressed during saccades. If the pickup of information from the optic array were suspended during saccades, this would be similar to closing the eyes for an equivalent period. Generally, sway is greater when the eyes are closed, relative to when they are open (e.g., Edwards, 1946); hence the prediction of increased sway during visual activities that require saccades.

We know of four studies that have assessed the effects of eye movements on body sway. White et al. (1980) argued that saccadic suppression should lead to increased sway during eye movements. To test this prediction, they instructed participants to alternate gaze between two target lights that were separated by 4° of horizontal visual

²Many studies have investigated relations between eye movements and locomotion to identify retinal or optical invariants used to control heading (e.g., Cutting, Alliprandini, & Wang, 2000; Wagner, Baird, & Barbaresi, 1981). However, posture during walking was not analyzed and it is unclear how these studies could contribute to the understanding of the relation between eye movements and stance.

angle. Participants were required to stand on one leg, and were instructed to fixate whichever light was illuminated. Three conditions were relevant to this study (in the other conditions, moving visual scenes were used to simulate the optical consequences of eye movements). In the control condition, only one target light was illuminated, producing stationary fixation. In two experimental conditions, the lights were illuminated alternately at 3 Hz or "aperiodically every few seconds" (p. 622). The dependent variable was the ratio of the power spectra of body sway in experimental and control conditions. The hypothesis that saccadic suppression would lead to an increase in body sway when the eyes were moving was not supported; there was no difference in the power spectra of sway between the fixation and saccade conditions. Postural data were obtained using a force platform; White et al. did not measure the position or motion of the eyes or head.

Oblak et al. (1985) also hypothesized that saccadic suppression would lead to increased body sway when the eyes were moving. Standing participants fixated a stationary target, or used saccades to fixate successively target lights to the left and right of center, which were illuminated one at a time, alternating at 0.5 Hz. Oblak et al. used electromyography to confirm that participants executed eye movements, but they did not analyze their eye movement data. Data obtained from a force platform were used to compute the mean radius of sway (the root mean square of deviations from the mean position). The hypothesis that sway would increase during eye movements was not supported. On the contrary, during eye movements there was a significant reduction in sway, relative to sway during stationary fixation. This finding is intriguing, but it cannot be taken at face value. The main reason is that Oblak et al. did not report the distance or separation of the target lights, or the amplitude of gaze shifts required to change fixation between lights; thus, we do not know whether the required gaze shifts tended to elicit head rotation (they did not measure head rotation). Head rotation is a problem for three reasons. First, it makes it more difficult to understand the role of eye movements, *per se*, in postural control. Second, it tends to introduce nonpostural motion of the head that complicates interpretation of postural measurements. Third, head rotation may bring into play the so-called vestibulo-ocular reflex (e.g., Steinman & Collewyn, 1980), which could complicate interpretation of both visual and postural behavior. For these reasons, and because we were interested in relations between postural control and eye movements, *per se*, in this study we used motion stimuli that typically elicit eye movements without head rotation.

Kikukawa and Taguchi (1985) also found that body sway was decreased during viewing of a moving visual target (this appeared to be true for healthy participants, but not for a group of participants with peripheral vestibular disorders). The reduction in sway appeared to be concentrated in the medio-lateral (ML) sway axis. Kikukawa and Taguchi recorded motion of the center of pressure (COP) during stationary fixation, and when participants looked at two targets that were lit alternately. Here again the reduction in body sway during eye movements cannot be taken at face value, for several reasons. The amplitude of required eye movements

(20°) was great enough to elicit movements of both the eyes and the head. In addition, the authors provided no information about the appearance of the visual stimuli. They also did not report the number or duration of trials, or inferential statistical tests on their effects.

Hunter and Hoffman (2001) measured body sway when participants fixated a stationary dot, and when they were instructed to shift gaze between several dots that appeared sequentially in different locations. Hunter and Hoffman measured the positional variability of the ML component of the COP and found that it was greater in the sequential condition than during stationary fixation. They interpreted this result in terms of "interference between the processing of visual information for the task and for the control of posture" (p. 45). However, two aspects of their methodology raise questions about the generality of their finding. First, they used heel-to-toe stance; this is not only unrepresentative of ordinary stance, but was also relatively novel for their participants, possibly requiring novel and inadequately practiced compensatory strategies. Second and perhaps more important, their eye movement condition required shifts in gaze of up to 54°. As noted earlier, when gaze is shifted more than 15°, eye movements typically are supplemented by rotation of the head (Hallett, 1986). Thus, in Hunter and Hoffman's study, it is very likely that head movements were used to fixate the targets (head movements were not measured). This means that the measured increase in COP variability during eye movements may have been an artifact of the use of head movements to facilitate shifts in gaze between the widely spaced targets.

This study differs from previous studies in several respects. To increase representativeness, stance was bipedal, with the feet side by side rather than heel to toe. The angular displacement of our moving targets was within the range that normally elicits shifting of gaze without rotation of the head (White et al., 1980). We did this because head rotation would tend to alter motion of the torso, which would complicate our effort to understand relations between eye movements and stance. Unlike any of the studies reviewed here, we directly measured head motion. This allowed us to determine whether head rotation was used in the presence of moving visual targets. We also conducted separate analyses of postural motion in the AP and ML axes (Hunter & Hoffman, 2001).

Summary and Predictions

If postural control competes with suprapostural activity for limited central processing resources (e.g., Teasdale et al., 1993; Woollacott & Shumway-Cook, 2002), then there should be degradation in postural control during eye movements that should be expressed as an increase in body sway (Hunter & Hoffman, 2001). Alternatively, if sway is unchanged, then there should be degradation in the accuracy of eye movements (e.g., relative to eye movements made in the absence of postural control actions). By contrast, if body sway is modulated to facilitate the achievement of suprapostural tasks (Stoffregen et al., 2000; Stoffregen et al., 1999), then

there should be a decrease in sway during visually guided eye movements (relative to stance during stationary fixation, and relative to stance during eye movements that are not visually guided), because accurate changes in the direction of gaze are easier when motion of the head and body is reduced. We assume that more precise control of the eyes is required to change the direction of gaze than to maintain stationary fixation. Previous studies have not directly contrasted these competing hypotheses and have provided ambiguous or inconsistent results. Critically, previous research has not adequately controlled for the possible influence of head rotation on gaze control or on measured body sway.

In these experiments, participants shifted their gaze between target positions, moved their (closed) eyes in time to a metronome, and held their eyes steady (during fixation of a stationary target, or with eyes closed). We predicted that (a) the amplitude and frequency of eye movements would match the amplitude and frequency of target motion (that is, we predicted that participants would successfully track the dot), (b) during visually guided eye movements, the variability of body sway would be reduced (relative to sway during fixation of stationary targets); and (c) during eye closure, posture would not be influenced by the presence or absence of eye movements. Previous research relating posture to vision has sometimes found trial effects (e.g., Pagulayan, Hayes, & Stoffregen, 2001). For this reason, in this study we analyzed the data for possible trial effects. However, we did not make any predictions about possible trial effects.

EXPERIMENT 1

There were four conditions in Experiment 1. In the stationary target condition, participants were asked to fixate a stationary target for the duration of each trial. In the moving target condition, two dots appeared on the screen sequentially and participants were asked to shift their gaze so as to look at whichever dot was visible at any given moment. We assumed that viewing of the stationary target would require less precise control of the eyes than viewing of the moving target. On this basis, we predicted that body sway variability would be reduced in the moving target condition, relative to sway when the target was stationary. The remaining conditions permitted us to determine whether any effects of eye movements on stance were related to the visual guidance of eye movements, or to the physical movement of the eyes, *per se*. In the closed moving condition, participants were instructed to engage in oscillatory, lateral eye movements during eye closure.³ Sway in this condition was compared to a condition in which the eyes were closed and stationary (closed stationary). When

³Oblak et al. (1985) included a condition where eye movements were made with eyes closed, but did not report any basis for pacing of frequency of these movements. Electromyography confirmed that participants moved their eyes as instructed. However, Oblak et al. did not report inferential statistics involving sway during eye movements with the eyes closed.

the eyes are closed, eye movements are not visually guided, that is, eye movements are not organized or evaluated with respect to targets in the environment, and so small variations in body sway should not influence such eye movements. A finding that body sway was influenced by eye movements during eye closure could undermine our assertion that the relation between sway and eye movements is functional. There was not an obvious reduction in cognitive demand in the eyes-closed condition. This is because we required participants to move their eyes in time with a metronome, which constrained the timing (but not the direction or amplitude) of eye movements. The metronome also had the benefit of ensuring that the frequency of eye movements was the same in eyes-open and eyes-closed conditions.

Separate measurement of head and torso position permitted us to evaluate several hypotheses. First, we could determine whether eye movements influenced only torso motion or motion of both the torso and head. Second, the collection of data on head position allowed us to determine whether participants rotated their heads. Given the small amplitude of gaze change needed, this was unlikely; however, it was important to evaluate the possibility.

Method

Participants. Fourteen undergraduate students (8 men, 6 women) from the University of Cincinnati participated in exchange for course credit. Participants reported no history of disease or malfunction of the vestibular apparatus, or of postural instability, recurrent dizziness, or falls. Due to apparatus constraints, participant height was limited to a maximum of 183 cm. Height ranged between 157.5 cm and 183 cm ($M = 170$ cm). Age ranged from 18 to 29 years ($M = 20$ years). Three participants had corrected vision (glasses or contacts). Participants were treated in accordance with the *Ethical Principles of Psychologists and Code of Conduct* (American Psychological Association, 1992).

Apparatus. Postural sway was recorded using a 6-df (degrees of freedom) magnetic tracking system (Flock of Birds, Ascension Technologies, Inc., Burlington, Vermont). One receiver was attached to a bicycle helmet worn by the participant, while a second receiver was attached to the skin between the shoulders (approximately at the seventh cervical vertebra) using cloth medical tape. Each receiver was sampled at 25 Hz, and the data were stored on a computer for later analysis. Visual stimuli were generated using PsyScope (Cohen, MacWhinney, Flatt, & Provost, 1993), and presented on a Macintosh G3 computer with a 43 cm Apple Studio Display.

Procedure. The experiment was conducted at the University of Cincinnati. The visual target consisted of a filled red circle on a white background. Luminance of the background was approximately 108.44 cd/m^2 , and luminance of the target was approximately 26.07 cd/m^2 . The contrast ratio was approximately 1:4. Participants stood with their eyes 100 cm from the display. At this distance, the target cir-

cles subtended approximately 1.15° of visual angle. In the stationary target condition, the visual target appeared in the center of the display and remained there for the duration of the trial. In the moving target condition, the target was presented in two positions, alternating between positions at 0.583 Hz to produce apparent motion. The target first appeared 9.75 cm to the left of the center of the display for 1 sec, at which point it disappeared, reappearing approximately 9.75 cm to the right of the center of the display, where it was again visible for 1 sec (maximum displacement approximately 19.5 cm, subtending 11° of visual angle in the horizontal plane). The 11° gaze shifts required in the moving target condition were well within the range that typically is accomplished with eye movements alone, that is, without supporting head movements (Hallet, 1986). Participants were shown an example of the moving target condition to ensure they fully understood the task.

In the third condition (closed moving), participants were instructed to move their eyes while they were closed. They were asked to move their eyes with the same amplitude as in the moving target condition (they were allowed to practice eyes-closed eye movements after viewing the stimulus for the moving target condition). Eye movements were paced to the sound of a metronome, which emitted a tone every 1.715 sec. Participants were instructed to move their eyes once at each tone, so that a full cycle (i.e., two movements) occurred at a frequency of 0.583 Hz. We sought to reproduce the 0.5 Hz used in previous studies, but 0.583 was the lowest frequency that our metronome could produce. This fact dictated the frequency of tones in the closed moving condition and, therefore, in the moving target condition. In the fourth condition (closed stationary), participants were instructed to close their eyes but keep them pointing straight ahead.

Each participant performed 12 trials (three in each condition), each of which lasted 65 sec. Condition order was counterbalanced across participants. Participants donned the bicycle helmet with the receiver attached to the back of it. An experimenter attached the second receiver. Participants were asked to stand approximately 100 cm from the display, with their feet together. The display was adjusted so that the top of the screen was approximately level with the participant's eyeheight. In all trials, participants were given the option of letting their arms hang at their sides, putting their hands in their pockets, or holding their hands clasped in front of or behind them. Whichever position they chose, they were asked to keep the same position for each trial, and not to move their hands during trials.

In conformity with University of Cincinnati institutional review board requirements, participants were required to sit and take a break after the first six experimental trials. This was done to minimize the possibility of fatigue or other adverse side effects of prolonged stance (Smart, Pagulayan, & Stoffregen, 1998).

Results

The dependent variables were the positional variability of the head and torso in fore-aft and lateral motion. These were operationalized as the standard deviation

of the head and torso displacements, analyzed separately for the AP and ML axes. The independent variable was condition (stationary target, moving target, closed stationary, closed moving). Separate analyses of variance (ANOVAs) were conducted on AP and ML motion of the head, and on AP and ML motion of the torso. Summary data (collapsed across trials) are presented in Figure 1. Data from representative trials are presented in Figure 2.

Torso ML. The main effect of condition was significant, $F(3, 39) = 22.39, p < .05$, partial $\eta^2 = 0.63$.⁴ The main effect of trial was not significant, $F(2, 26) = 1.36, p > .05$, nor was the Condition $\times$ Trial interaction, $F(6, 78) < 1, ns$. Planned t tests (using a criterion alpha of .0167)⁵ revealed that there was less variability in the moving target condition ($M = 0.216$ cm) than in the stationary target condition ($M = 0.294$ cm); $t(13) = 4.80, p < .0167$, as predicted. There was also less variability in the moving target condition than in the closed moving condition ($M = 0.385$ cm); $t(13) = 6.68, p < .0167$, as predicted. There was less variability in the stationary target condition than in the closed stationary condition ($M = 0.437$ cm); $t(13) = 3.64, p < .0167$, replicating classical effects (e.g., Edwards, 1946). Finally, variability in the closed stationary condition did not differ from that in the closed moving condition, $t(13) = 2.05, p > .0167$. Thus, the influence of eye movements on torso motion occurred only when the eyes were open.

Torso AP. The main effect of conditions was significant, $F(3, 39) = 34.07, p < .05$, partial $\eta^2 = 0.72$. The main effect of trial was not significant, $F(2, 26) = 2.49, p > .05$, but the Trial $\times$ Condition interaction was significant, $F(6, 78) = 2.39, p < .05$, partial $\eta^2 = 0.16$. The Trial $\times$ Condition interaction is illustrated in Figure 3. The interaction seems to indicate that when the eyes were moving, postural variability followed an inverted U, being greater in Trial 2 than in Trials 1 and 3. When gaze was stationary, postural variability decreased over trials (when the eyes were open), or was constant over trials (when the eyes were closed). We did not predict this interaction, and we do not have a clear interpretation of it.

Planned comparisons on the main effect of conditions revealed that the moving target condition ($M = 0.234$ cm) did not differ from the stationary target condition, $M = 0.237$ cm, $t(13) = 0.165, p > .0167$. The moving target condition was significantly less variable than the closed moving condition, $M = 0.337$ cm, $t(13) = 6.51, p < .0167$, as predicted. The stationary target condition was significantly less variable than the closed stationary condition, $M = 0.363$ cm, $t(13) = 6.74, p < .0167$, replicating classical effects (e.g., Edwards, 1946; Riley et al., 1997). The closed stationary condition did not differ from the closed moving condition, $t(13) = 2.28, p > .0167$.

⁴The effect size was computed using SPSS and reporting the partial η^2 statistic.

⁵The criterion alpha was selected using the Bonferroni adjustment, taking into account that we conducted some statistical comparisons between Experiments 1 and 2 (see later).

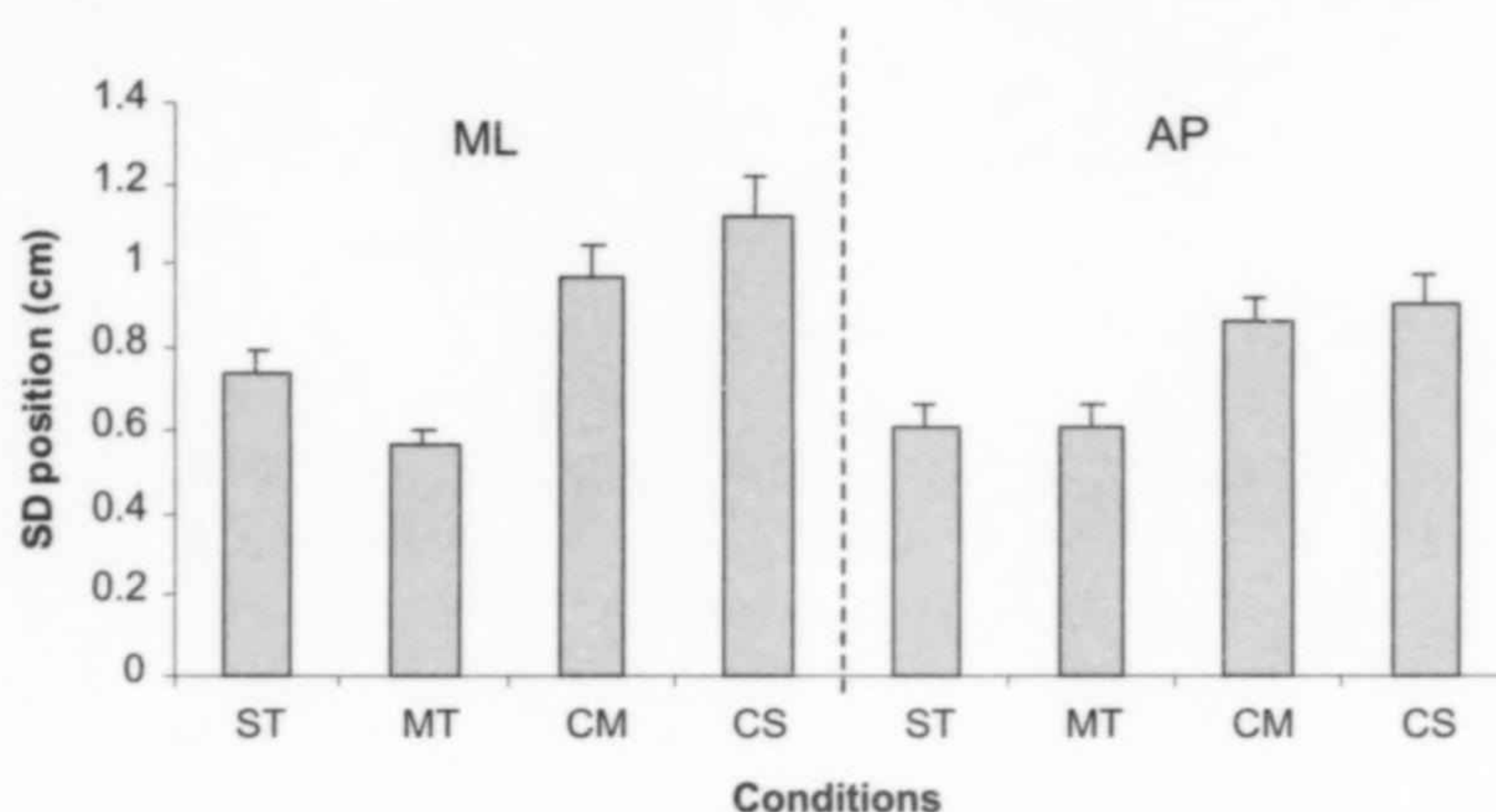
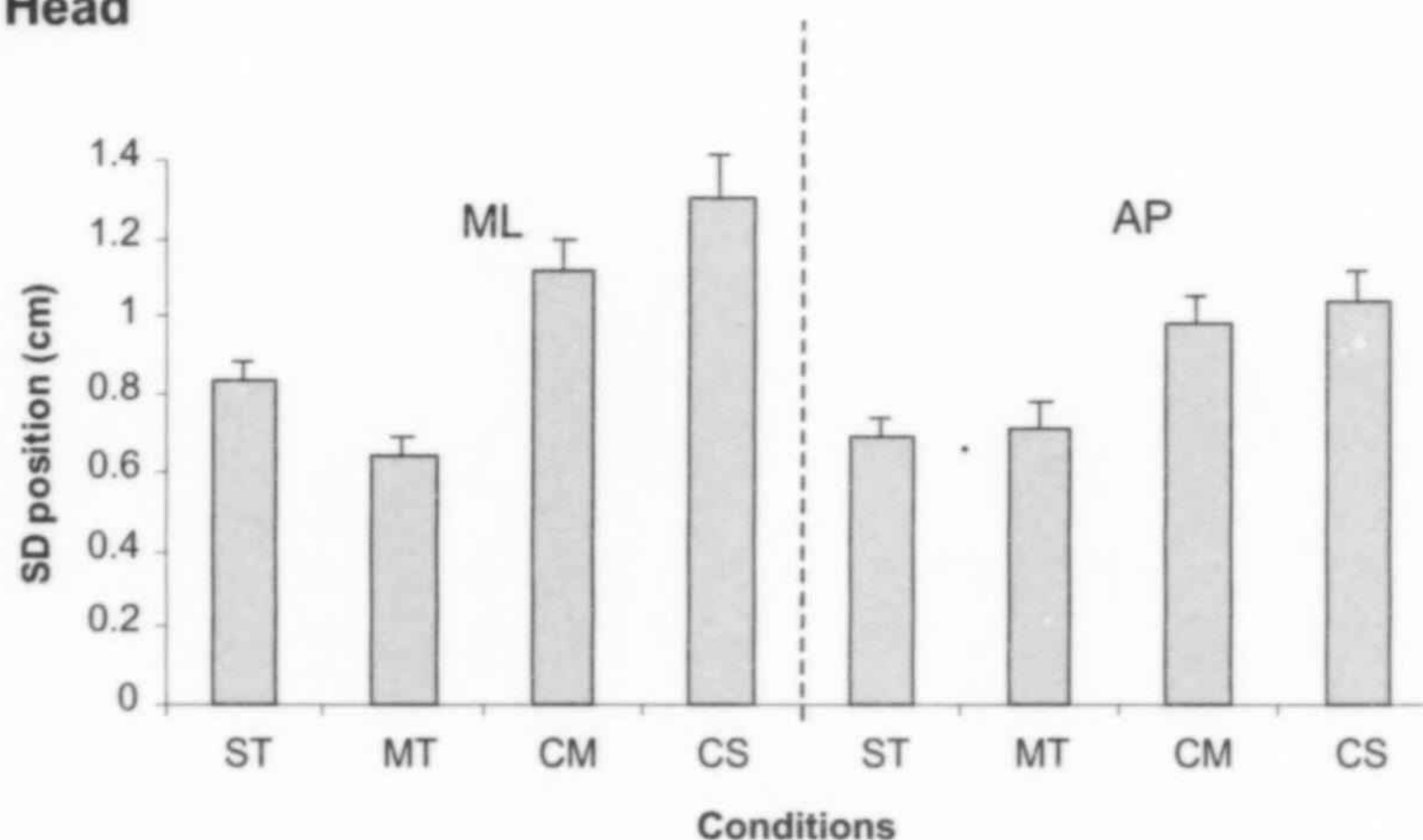
Torso**Head**

FIGURE 1 Means of the positional variability of the head and torso in the AP and ML axes, Experiment 1. ST = stationary visual target; MT = apparent motion of the visual target at 0.583 Hz; CM = eyes closed with instructions to move the eyes in time with the metronome at 0.583 Hz; CS = eyes closed with instructions to hold the eyes stationary. Error bars represent the standard error of the mean.

Head ML. The main effect of condition was significant, $F(3, 39) = 22.34$, $p < .05$, partial $\eta^2 = 0.63$. The main effect of trial was not significant, $F(2, 26) = 1.64$, $p > .05$; nor was the Condition $\times$ Trial interaction, $F(6, 78) < 1$, *ns*.

Planned *t* tests revealed that, as predicted, variability of head motion during the moving target condition, $M = 0.252$ cm, was significantly less than during the stationary target condition, $M = 0.325$ cm, $t(13) = 3.86$, $p < .0167$. As predicted, variability of head motion during the moving target condition was significantly less

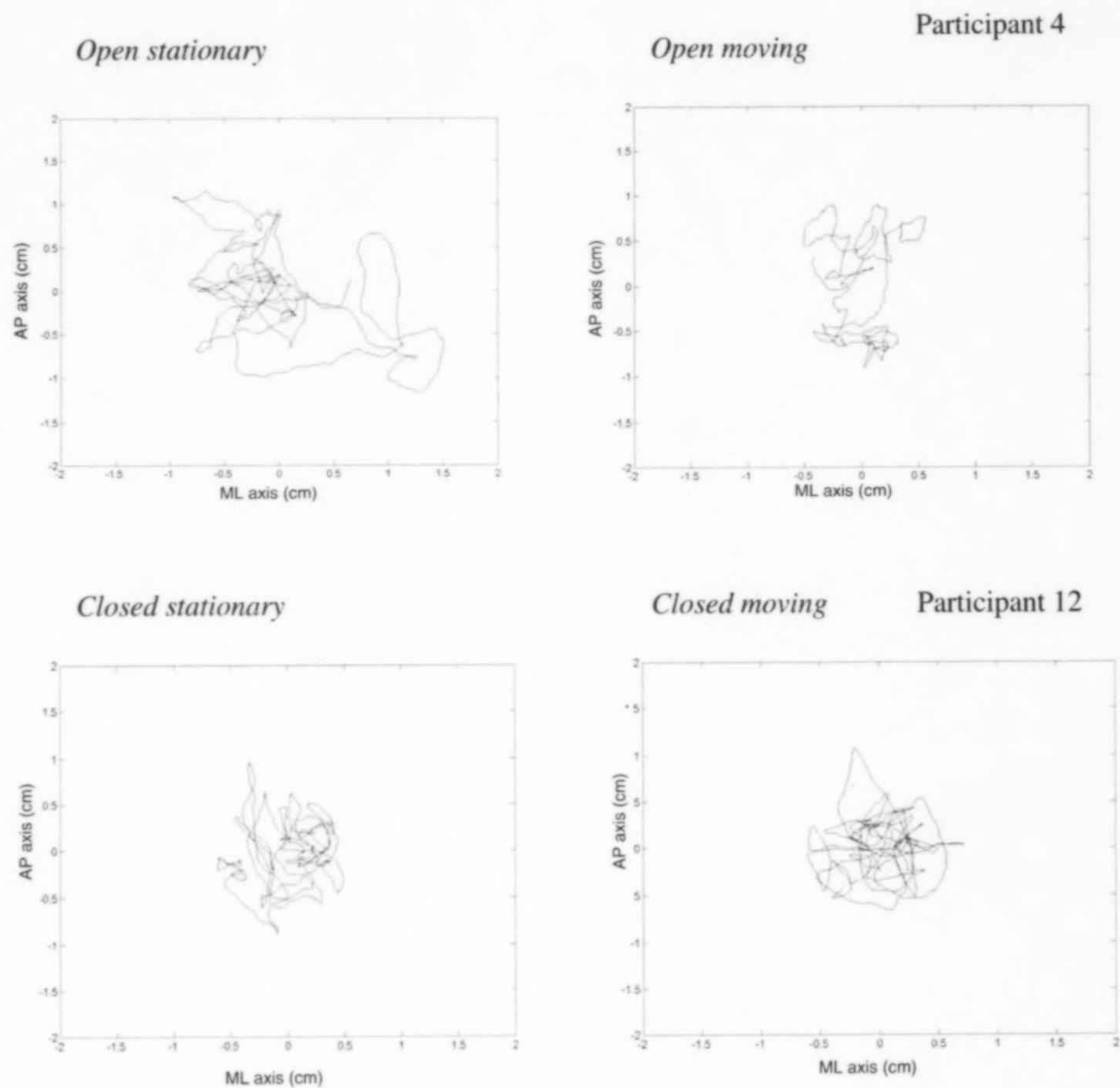


FIGURE 2 Representative head/torso position data for one participant in Experiment 1.

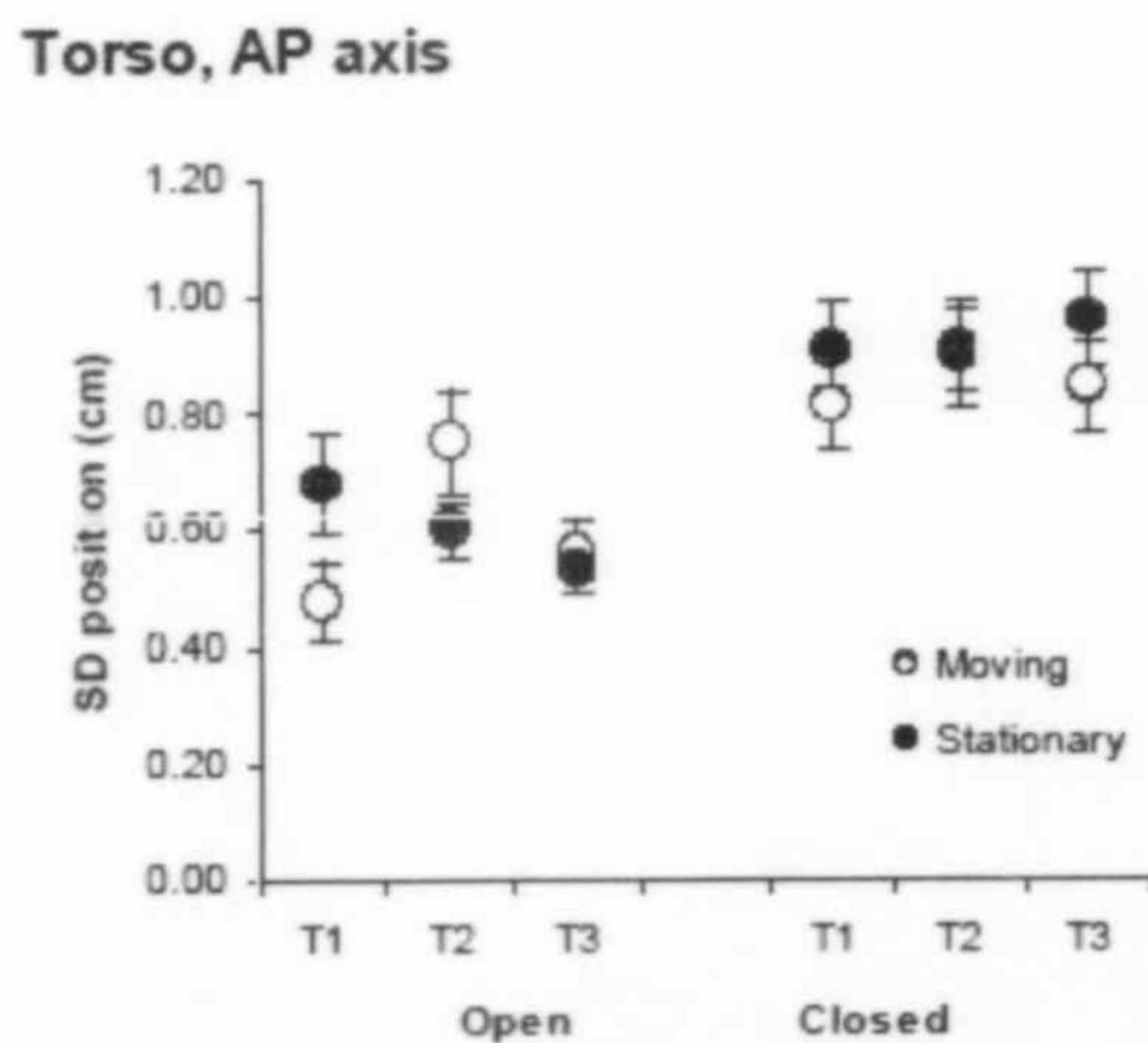


FIGURE 3 The significant Trial $\times$ Condition interaction, Experiment 1.

than during the closed moving condition, $M = 0.435$ cm, $t(13) = 7.08$, $p < .0167$. In addition, variability of head motion during the stationary target condition was significantly less than during the closed stationary condition, $M = 0.511$ cm, $t(13) = 3.82$, $p < .0167$, replicating classical effects (e.g., Edwards, 1946). Finally, ML head motion during the closed moving condition was not significantly different than during the closed stationary condition, $t(13) = 2.26$, $p > .0167$, confirming our prediction.

Head AP. The main effect of condition was significant, $F(3, 39) = 30.38$, $p < .05$, partial $\eta^2 = 0.70$. The main effect of trial was significant, $F(2, 26) = 4.07$, $p < .05$, partial $\eta^2 = 0.24$, but the Trial $\times$ Condition interaction was not significant, $F(6, 78) = 2.09$, $p > .05$. Means and standard deviations for the trials were as follows: Trial 1, $M = 0.81$ cm, $SD = 0.36$ cm; Trial 2, $M = 0.92$ cm, $SD = 0.37$ cm; and Trial 3, $M = 0.83$ cm, $SD = 0.33$ cm.

Planned comparisons on the main effect of conditions revealed that AP motion of the head did not differ during the moving target and stationary target conditions, $M = 0.281$ and 0.266 cm, respectively; $t(13) = 0.575$, $p > .0167$. AP head motion during the moving target condition was significantly reduced relative to the closed moving condition, $M = 0.389$ cm, $t(13) = 5.43$, $p < .0167$. During the stationary target condition, AP head motion was significantly less than during the closed stationary condition, $M = 0.412$ cm, $t(13) = 7.83$, $p < .0167$, replicating classical effects (e.g., Edwards, 1946). During the closed stationary condition, AP head motion did not differ from the closed moving condition, $t(13) = 1.95$, $p > .0167$. Finally, post hoc t tests on the main effect of trial revealed that AP motion of the head was greater during Trial 2 than during either Trial 1, $t(55) = 1.99$, $p < .05$, or Trial 3, $t(55) = 2.18$, $p < .05$. Trials 1 and 3 did not differ, $t(55) < 1$, ns .

Head rotation. We computed head rotation about the vertical axis. This allowed us to evaluate the possibility that participants used head movements to maintain gaze on the moving target, rather than (or in addition to) eye movements. Means and standard deviations for the conditions were as follows: stationary target, $M = 1.08^\circ$, $SD = 1.08^\circ$; moving target, $M = 1.31^\circ$, $SD = 1.22^\circ$; closed moving, $M = 0.48^\circ$, $SD = 0.85^\circ$; closed stationary, $M = 1.24^\circ$, $SD = 0.45^\circ$. An ANOVA revealed that there was not a significant effect of condition on head rotation around the vertical axis, $F(3, 123) < 1$, ns .

Discussion

For both the head and torso, sway in the ML axis was reduced when the target moved, relative to when it was stationary. Sway in the closed moving condition was less variable than in the closed stationary condition, but this was true only for head ML. That is, there was an effect on the head, but not on the torso. Variability of head motion in the moving target condition was less than in the closed moving

condition, for both head and torso, in both axes. Finally, there was no difference among conditions in the rotation of the head around its vertical axis.

Postural Stabilization of Visually Guided Eye Movements

The results from Experiment 1 confirmed most of our predictions. Postural sway variability in the ML axis was reduced when looking at a moving target, relative to sway when looking at a stationary target. Experiment 1 provides support for the claim that the control of posture can be influenced by suprapostural visual tasks. The purpose of this experiment was to investigate relations between eye movements and body sway under conditions in which other factors, such as target distance and the cognitive content of tasks were held constant. Together with the findings of Oblak et al. (1985), Experiment 1 makes it clear that visually guided eye movements alone are sufficient to influence the organization of body sway.

Head Rotation

There was no effect of condition on rotation of the head around its vertical axis. That is, participants did not use head rotation differentially across conditions. This means that the most likely cause of the postural effects of target motion is eye movement per se. It may be important that the lack of head rotation effects corresponded with the presence of head and torso effects in the ML axis, indicating that the level of fine-tuning of postural changes with respect to the suprapostural task. These results suggest the possibility that body sway (in the ML axis) might be used to stabilize eye movements that are less than 11° in amplitude, with head rotation (perhaps augmented by sway) being used when eye movements exceed 11° .

Eye Movements When the Eyes Were Closed: Torso Motion

The main purpose of asking participants to move their eyes while they were closed was to determine whether postural control would be influenced by eye movements that were not visually guided. In assessing this possibility, the central comparison was between torso motion with the eyes closed and stationary, and torso motion with the eyes closed and moving. When the eyes were closed, there was not a significant difference in the variability of torso motion in the eyes-stationary and eyes-moving conditions in either the AP or ML axes. This contrasts with the influence of eye movements on torso motion when the eyes were open: Visually guided eye movements produced a reduction in torso motion, but eye movements that did not rely on visual guidance had no effect on torso motion. This contrast supports our argument that the relation between postural sway and eye movements is func-

tional, that is, that posture is used to facilitate the control of eye movements that are visually guided.

The variability of torso position was reduced when eye movements were visually guided (the moving target condition), relative to when they were not (the closed moving condition). This confirms that the differences in torso motion between the moving target and stationary target conditions were related to the control of the visual system relative to the visible environment (i.e., to visual performance), and not to the presence of eye movement, *per se*.

Eye Movements When the Eyes Were Closed: Head Motion

When the eyes were closed eye movements did not influence motion of the torso, but they did influence motion of the head. In the ML axis there was a significant decrease in head motion during the closed moving condition, relative to sway in the closed stationary condition. This effect confirms that participants actually modified their behavior in response to our instruction to move the eyes while they were closed.

The fact that there was an effect on ML head motion of eye movements when the eyes were closed was contrary to our prediction. However, the direction of the effect was contrary to predictions that could be motivated by the idea that postural and ocular control compete for a limited pool of central processing resources. The resource competition view can predict reduction in performance of one or both of two simultaneous tasks and, if the two tasks do not exhaust the available resources, it can predict that performance of the combined tasks will be equivalent to the performance of each task alone. But the resource competition view does not appear to offer any basis for predicting that performance of either task will improve when they are combined.

The reduction in variability of ML head motion during eyes-closed eye movements may suggest some relation between head motion and the mechanics of the oculomotor system. However, other interpretations are possible. One interpretation arises from the fact that in the closed moving condition eye movements were paced to the sound of a metronome. In this condition, participants were obliged to pay attention to the sound of the metronome, independent of their need to move the eyes. Listening to the metronome may have constituted a suprapostural task. It is possible that the reduced variability of ML head motion facilitated the task of listening to the metronome; such an effect would be functional. That is, participants may have engaged in postural stabilization of listening. Additional research will be required to determine whether changes in ML head motion are related to listening, to the mechanics of nonvisual eye movements, or to some other cause.

Another interpretation of the condition effect on ML head motion in the absence of an effect on torso motion relates to the information needed to control eye movements. To produce eye movement in phase with the metronome, participants

needed information about how their eyes were moving. With the eyes closed, such information was not available visually, and so it seems likely that the required information would have been obtained proprioceptively, for example, in feedback from ocular muscles moving the eyes in the medio-lateral direction. The pickup of such information might be complicated by simultaneous motion of the head in the same direction: Proprioceptive information about head movement would be irrelevant to the eye movement task. For this reason, a reduction in head motion (especially in the ML axis) may have made it easier for participants to detect the proprioceptive information needed to execute the novel task of moving their eyes laterally during eye closure. It may be that participants reduced head movement to better perceive (and control) the motion of their eyes with respect to the metronome, similar to the reduction in head rotation that has been observed during various locomotor tasks (e.g., Berthoz, 1990).

EXPERIMENT 2

In Experiment 2, we measured eye movements, using electro-oculography (EOG). EOG is the only technology that permits measurement of movements when the eyes are closed as well as when they are open. Our main purpose in Experiment 2 was to confirm that participants moved their eyes when instructed to do so and to determine the amplitude of eye movements. The conditions and manipulations were the same as in Experiment 1 and, accordingly, we made the same predictions about relations between body sway and visually guided eye movements.

Method

Participants. Fourteen undergraduates from the University of Minnesota participated as volunteers; none had participated in Experiment 1. Participants reported no history of disease or malfunction of the vestibular apparatus, or of postural instability, recurrent dizziness, or falls. We did not restrict participation on the basis of height. Rather, the height of the display monitor was adjusted individually for participants. Participants' height ranged between 152.4 cm and 195 cm ($M = 173.1$ cm). Age ranged from 19 to 25 years ($M = 21$ years). Three participants had corrected vision (glasses or contacts).

Apparatus. Displays were created using PsyScope, as in Experiment 1, and were presented on a color flat screen monitor measuring 50.8 cm diagonally. Eye position and movement were measured using a standard EOG system (Biopac Systems, Inc., Goleta, California). The EOG system was positioned immediately to the participant's right. This was done because the cables connecting the electrodes to the EOG electronics unit were 114 cm long (this fact is important to our interpretation of some of the results). The EOG electronics unit was connected to a PC

that sat on a desk on the participant's left. The cable connecting the electronic unit to the computer passed in front of the participant. Eye position was sampled at 62.5 Hz. Postural data (head and torso motion) were measured using the Flock of Birds, with each receiver sampled at 47 Hz.

Procedure. The experiment was conducted at the University of Minnesota. The conditions and procedure were the same as in Experiment 1, except for the use of the EOG system. Participants were asked to stand with their toes on a line on the floor, so that their eyes were approximately 100 cm from the center of the monitor. The EOG system was calibrated before each trial, using the method recommended by the manufacturer.

In conformity with University of Minnesota institutional review board requirements, participants were required to sit and take a break after the first six experimental trials. This was done to minimize the possibility of fatigue or other adverse side effects of prolonged stance (Smart et al., 1998).

Results

Postural motion. The data are summarized in Figures 4 and 5. We conducted separate repeated measure ANOVAs on data for the AP and ML axes, and for the head and torso. For each significant effect in the ANOVAs, planned *t* tests were conducted. These *t* tests were not independent, and for this reason, we applied the Bonferroni inequality to adjust the criterion alpha. For each ANOVA, four *t* tests were planned, yielding a criterion alpha for each test of 0.0167, as explained earlier.

Torso ML. The main effect of condition was significant, $F(3, 39) = 4.27, p < .05$, partial $\eta^2 = 0.25$. The main effect of trial was significant (Figure 5), $F(2, 26) = 8.20, p < .05$, partial $\eta^2 = 0.39$; but the Condition $\times$ Trial interaction was not significant, $F(6, 78) < 1, ns$. We did not predict significant main effects of trial on postural motion in Experiment 2. The meaning of these effects is considered in the Discussion section.

Planned *t* tests revealed that there was less variability in the moving target condition, $M = 0.122$ cm, than in the stationary target condition, $M = 0.160$ cm, $t(13) = 3.489, p < .0167$, as predicted. The moving target and closed moving conditions did not differ (closed moving $M = 0.138$ cm); $t(13) = 1.166, p > .0167$. The stationary target and closed stationary conditions also did not differ (closed stationary $M = 0.150$ cm), $t(13) = .897, p > .0167$, not replicating classical effects (e.g., Edwards, 1946; Riley et al., 1997). Finally, variability in the closed stationary condition did not differ from that in the closed moving condition, $t(13) = 1.254, p > .0167$. Thus, the influence of eye movements on torso motion occurred only when the eyes were open.

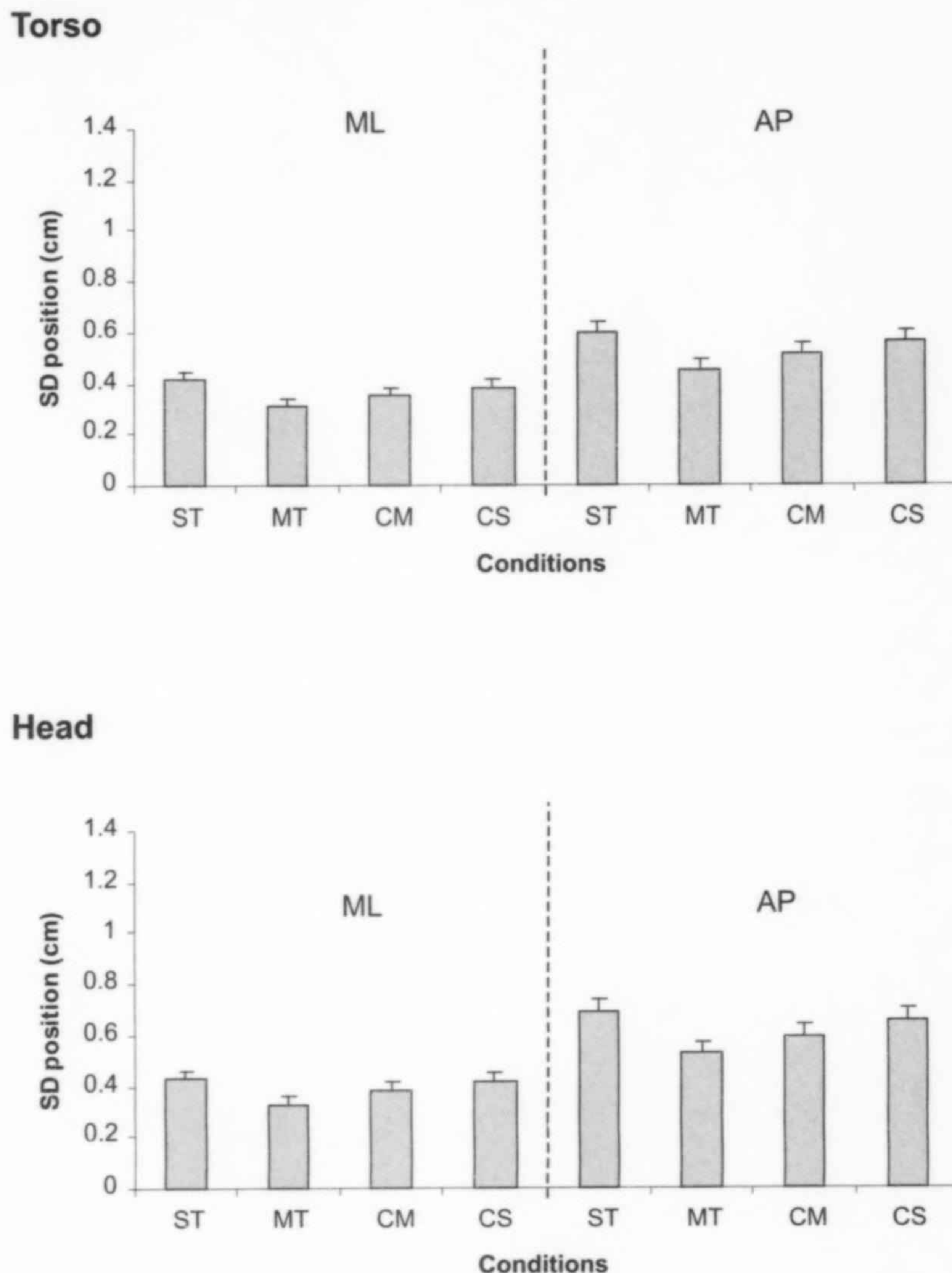


FIGURE 4 Means of the positional variability of the head and torso in the AP and ML axes, Experiment 2. ST = stationary visual target; MT = apparent motion of the visual target at 0.583 Hz; CM = eyes closed with instructions to move the eyes in time with the metronome at 0.583 Hz; CS = eyes closed with instructions to hold the eyes stationary. Error bars represent the standard error of the mean.

Torso AP. The main effect of condition was significant, $F(3, 39) = 4.33, p < .05$, partial $\eta^2 = 0.25$. The main effect of trial was significant (Figure 5), $F(2, 26) = 7.26, p < .05$, partial $\eta^2 = 0.36$, but the Condition $\times$ Trial interaction was not significant, $F(6, 78) < 1, ns$.

Planned comparisons on the main effect of condition revealed that motion in the moving target condition, $M = 0.178$, differed from the stationary target condition, $M = 0.238$ cm, $t(13) = 3.526, p < .0167$. Sway in the moving target condi-

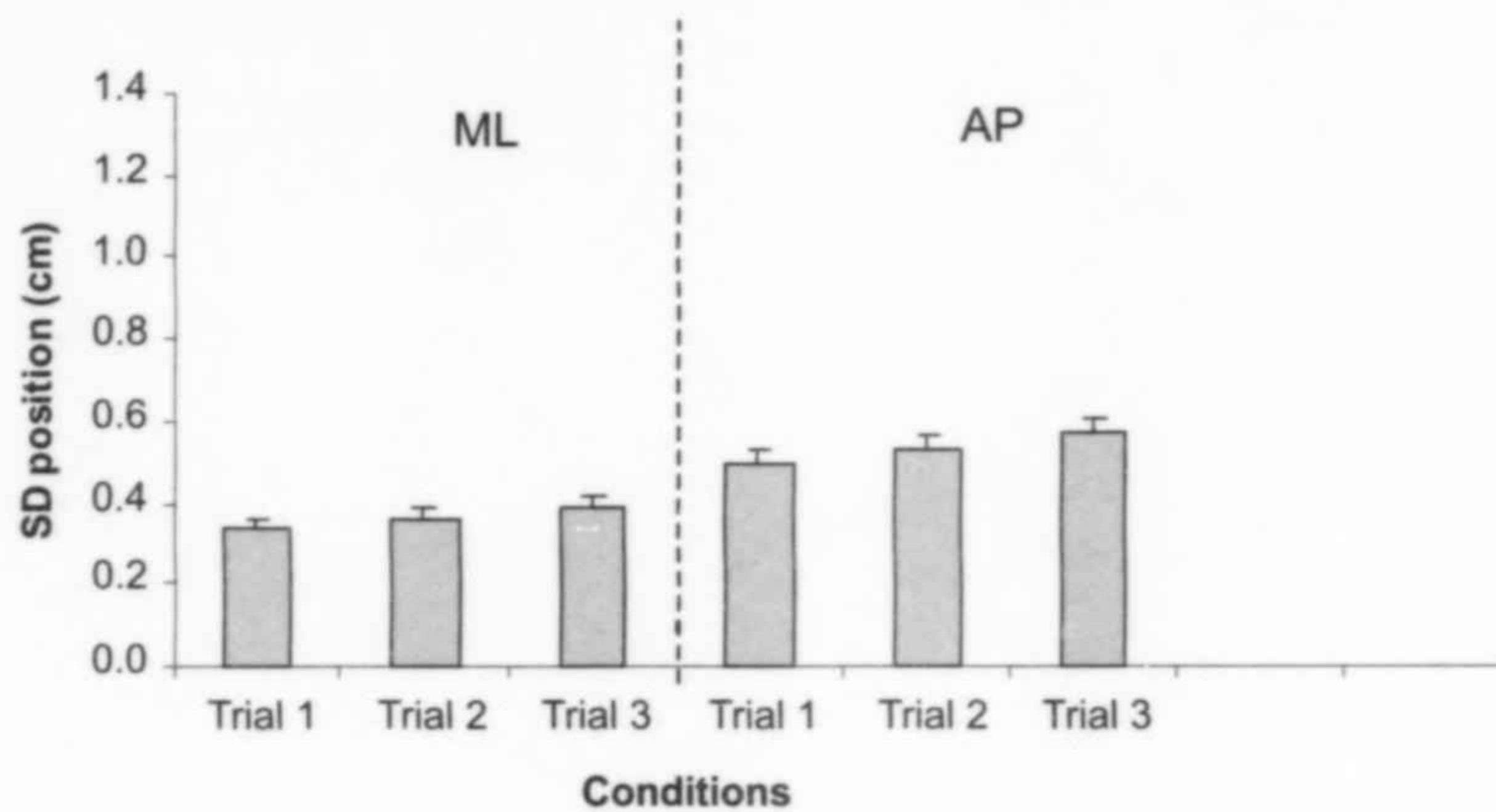
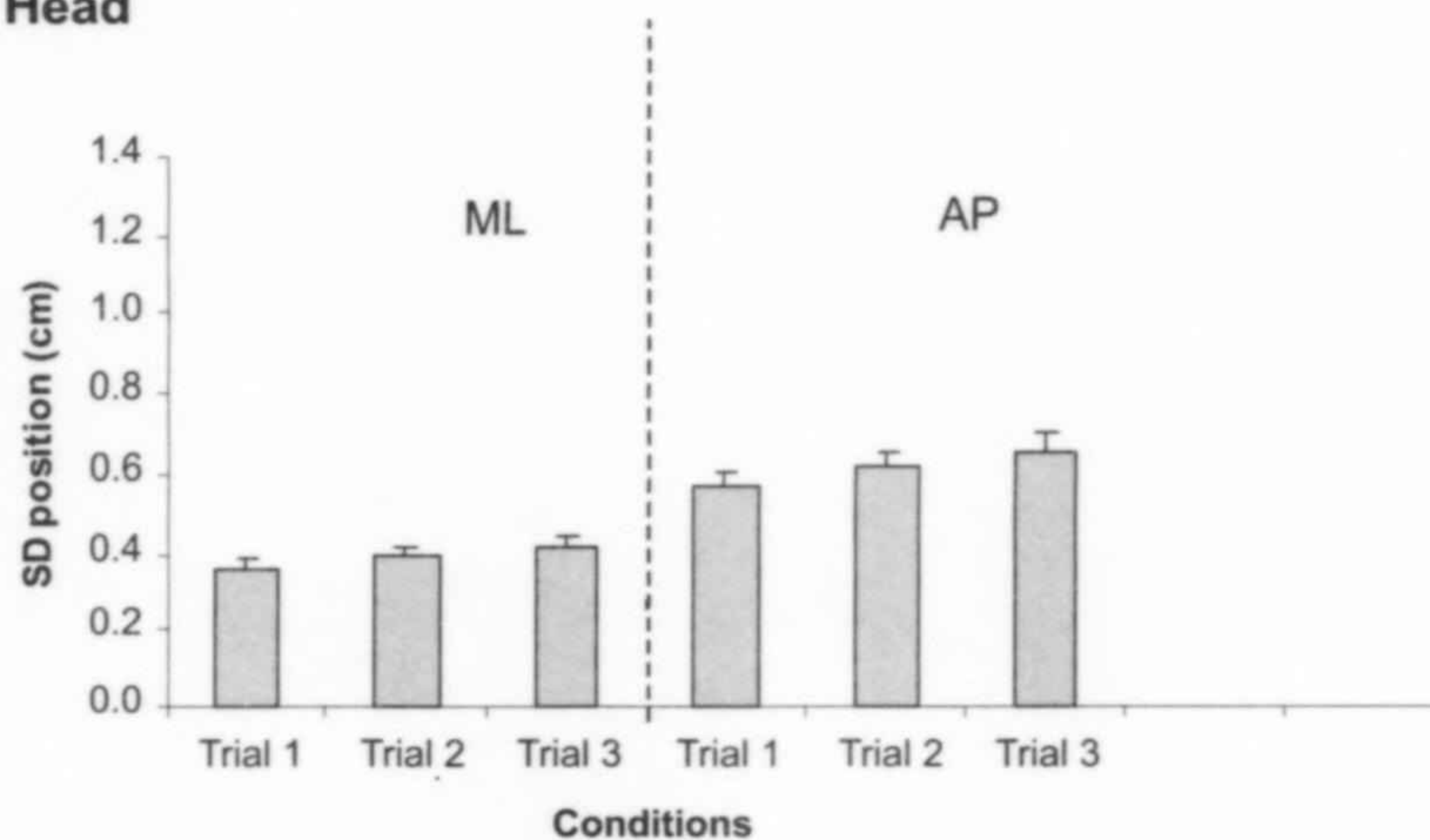
Torso**Head**

FIGURE 5 The significant main effects of trials, Experiment 2. A: Torso. B: Head. T1, T2, T3: Trials 1, 2, and 3, respectively. Error bars represent the standard error of the mean.

tion did not differ from the closed moving condition, $M = 0.201$ cm, $t(13) = 1.142$, $p > .0167$. Similarly, sway did not differ in the stationary target and closed stationary conditions, not replicating classical effects, $t(13) = 1.083$, $p > .0167$ (closed stationary $M = 0.219$ cm). Finally, as predicted, sway in the closed stationary condition did not differ from the closed moving condition $t(13) = 1.171$, $p > .0167$.

Head ML. The main effect of condition was significant, $F(3, 39) = 3.61$, $p < .05$, partial $\eta^2 = 0.22$. The main effect of trial was significant (Figure 5), $F(2, 26) = 5.55$, $p < .05$, partial $\eta^2 = 0.30$; but the Condition $\times$ Trial interaction was not significant, $F(6, 78) < 1$, ns.

Planned t tests revealed that, as predicted, variability of head motion during the moving target condition, $M = 0.131$ cm, was significantly less than during the stationary target condition, $M = 0.170$ cm, $t(13) = 3.552$, $p < .0167$. As previously, variability of head motion during the moving target condition did not differ compared to variability of head motion during the closed moving condition, $M = 0.149$ cm, $t(13) = 1.289$, $p > .0167$. In addition, variability of head motion during the stationary target condition was not significantly different from that of the closed stationary condition, $M = 0.161$ cm, $t(13) = .756$, $p > .0167$, again not replicating classical effects. Finally, ML head motion during the closed moving condition did not differ from that in the closed stationary condition, $t(13) = 1.002$, $p > .0167$.

Head AP. The main effect of condition was significant, $F(3, 39) = 3.70$, $p < .05$, partial $\eta^2 = 0.22$. The main effect of trial was significant (Figure 5), $F(2, 26) = 5.23$, $p < .05$, partial $\eta^2 = 0.29$, but the Trial $\times$ Condition interaction was not significant, $F(6, 78) < 1$, ns .

Planned comparisons on the main effect of condition revealed that AP motion of the head differed in the moving target and stationary target conditions, $M = 0.207$ and 0.271 , respectively; $t(13) = 3.524$, $p < .0167$. However, in the moving target and closed moving conditions, $M = 0.233$ cm, AP head motion did not differ, $t(13) = -1.212$, $p > .0167$. Similarly, in the stationary target and closed stationary conditions, $M = 0.255$ cm, AP head motion did not differ, $t(13) = .729$, $p > .0167$, nor did the closed stationary and closed moving conditions, $t(13) = 1.123$, $p > .0167$.

Comparison of Experiments 1 and 2. Our purposes in Experiment 2 were to show that participants moved their eyes when they were instructed to do so, that eye movements were similar in amplitude and frequency to the apparent motion of the visual targets, and to confirm that these effects corresponded to reductions in the variability of postural sway when participants were shifting their gaze (i.e., in the moving target condition), relative to sway when gaze was stationary (the stationary target condition) or when the eyes were closed (the closed stationary and closed moving conditions). With respect to each of these goals, Experiment 2 was successful.

In Experiment 2, sway did not differ when the eyes were closed (the closed stationary condition) relative to when they were open (the stationary target condition). This deviates from Experiment 1, and from classical findings that sway tends to increase when the eyes are closed. The absence of this effect in Experiment 2 is not directly relevant to the purposes of the experiment, as described here. However, the failure to replicate this classical effect is puzzling. In an attempt to understand this unusual result, we compared the data from the two experiments, in the same conditions. For each condition we conducted independent t tests for each body segment (head and torso) in each axis (AP and ML). In the closed stationary condition, each of the four t tests was significant: head AP, $t(13) = -5.07$, $p < .0167$; head ML, $t(13) = -7.512$, $p < .0167$; torso AP, $t(13) = -5.131$, $p < .0167$;

and torso ML, $t(13) = -6.917, p < .0167$. In each case, sway in Experiment 2 was less than in Experiment 1 (compare Figures 1 and 4). This was true also in the closed moving condition: head AP, $t(13) = -5.279, p < .0167$; head ML, $t(13) = -8.01, p < .0167$; torso AP, $t(13) = -5.084, p < .0167$; torso ML, $t(13) = -6.832, p < .0167$. These results indicate that in Experiment 2, sway with the eyes closed was reduced relative to typical situations (and relative to sway in Experiment 1).

Similar results were obtained in the eyes-open conditions. For the stationary target condition, there were significant reductions in sway in Experiment 2, relative to the same condition in Experiment 1, but only in the ML axis: head AP, $t(13) = -1.907, p > .0167$; head ML, $t(13) = -4.017, p < .0167$; torso AP, $t(13) = -2.124, p > .0167$; torso ML, $t(13) = -3.583, p < .0167$. For the moving target condition, sway in Experiment 2 was reduced relative to Experiment 1, for both the head and torso, but again only in the ML axis: head AP, $t(13) = -1.852, p > .0167$; head ML, $t(13) = -4.866, p < .0167$; torso AP, $t(13) = -1.719, p > .0167$; torso ML, $t(13) = -4.763, p < .0167$. Overall, our post hoc tests revealed that sway in Experiment 2 was reduced relative to sway in Experiment 1. We offer an interpretation of this effect in the Discussion section.

Head rotation. We computed head rotation about the vertical axis. This allowed us to evaluate the possibility that participants used head movements, rather than (or in addition to) eye movements, to maintain gaze on the moving target. Means and standard deviations for the conditions were as follows: stationary target, $M = 0.60^\circ, SD = 0.21^\circ$; moving target, $M = 0.63^\circ, SD = 0.29^\circ$; closed moving, $M = 0.59^\circ, SD = 0.20^\circ$; closed stationary $M = 0.73^\circ, SD = 0.39^\circ$. An ANOVA revealed that there was not a significant effect of condition on head rotation around the vertical axis, $F(3, 123) = 1.04, p > .05$.

Eye movements. Due to technical problems, eye movement data were dropped from three trials in the closed stationary condition, and from seven trials in the stationary target condition. In the stationary target and closed stationary conditions participants were instructed not to move their eyes. For these conditions, we calculated the standard deviation of horizontal eye position. For the stationary target condition, the mean standard deviation of eye position was 4.2° , whereas for the closed stationary condition it was 7.0° . In the moving target and closed moving conditions participants were asked to move their eyes. For these conditions, we first computed the mean eye position during each fixation (i.e., the period between successive eye movements), separately for fixation on the right and left sides. The difference in position between the mean left and right positions was considered to be the amplitude of each individual eye movement. Using these data, we calculated the mean and standard deviation of eye movement amplitudes for each trial. In the moving target condition, the mean amplitude of eye movements was 11.2° , and the standard deviation of this mean was 1.5° . In the closed moving

condition, the mean amplitude of eye movements was 73.6° , and the standard deviation of this mean was 9.0° .

We analyzed the frequency of eye movements. We did this by counting the total number of eye movements in each trial, and dividing by the duration of the trial. Across trials and participants, the mean and standard deviation of eye movement frequency were as follows: moving target condition, $M = 0.54$ Hz, $SD = 0.02$ Hz; closed movement condition, $M = 0.54$ Hz, $SD = 0.02$ Hz. On the basis of these data, we concluded that participants moved their eyes when requested to do so, and that in the moving target condition they moved them at the same amplitude and frequency as the visual targets.

Discussion

The eye movement data were supportive of our hypotheses. Participants moved their eyes when requested, and held them still when requested. Eye movements closely matched the frequency of stimulus motion, both with visual target motion (when the eyes were open), and with metronome pace (when they were closed). When the eyes were open, the angular amplitude of eye movements closely matched the angular amplitude of stimulus motion. When the eyes were closed, the angular amplitude of eye movements was greater than the instructed amplitude; this result is consistent with findings from previous studies (e.g., Kikukawa & Taguchi, 1985; Oblak et al., 1985), and suggests that a person's knowledge of eye movement amplitude is strongly dependent on visible referents, rather than being related to nonvisual referents (e.g., internal coordinate systems).

As in Experiment 1, head rotation was not used with moving visible targets. In addition, head rotation was not used when participants were instructed to move their eyes in time with the metronome. This is especially interesting given that eye movements were very large when the eyes were closed, $M = 73.59^\circ$, as opposed to those in the open movement condition, $M = 11.16^\circ$. Thus, we can conclude with some confidence that the differences in sway between moving target and stationary target conditions were not caused by differential rotation of the head around the vertical axis (i.e., in the plane of target motion).

With respect to the hypotheses that motivated our study, the postural data generally replicated the findings of Experiment 1. In some cases, the results of Experiment 2 can be seen as having been stronger than in Experiment 1. In Experiment 1, reductions in sway in the moving target condition were limited to head and torso motion in the ML axis. By contrast, in Experiment 2 such reductions were observed for both the ML and AP axes, for both the head and torso. In other cases, effects in Experiment 2 can be seen as having been weaker than in Experiment 1. In Experiment 1, sway was reduced during visually guided eye movements (the moving target condition) relative to sway during eye movements that were not visually guided (the closed moving condition) for both the head and torso in both the ML and AP axes. By contrast, in Experiment 2 no such reductions were observed.

One difference not related to our hypotheses was that overall sway did not increase when the eyes were closed. This most likely reflects caution on the part of participants, related to the proximity of the EOG apparatus (electronics unit) and/or the cable connecting the EOG unit to the PC. That is, we believe that participants reduced their overall sway so as to ensure that they did not bump into the experimental apparatus. A similar effect was reported by Stoffregen et al. (1999), who compared sway in a large room with sway when participants stood in a small booth (1 m by 0.8 m). In three experiments, they found that sway variability was reduced during stance in the booth relative to stance when the booth was absent. By varying the transparency of the booth walls, they manipulated the motion parallax and optical velocities created by body sway. Their results showed that the reduction in sway during stance in the booth was related to the physical size of the booth rather than to parameters of sway-generated optic flow, and they suggested that the reduction in sway might have arisen from participants' desire to avoid bumping into the walls.

A second notable difference was that in Experiment 2 the main effect of trial was significant for each of our dependent variables. These trial effects accounted for large portions of the variance; in some cases, larger than the portion accounted for by the condition effects. In each of the dependent variables, postural motion increased over trials. We did not predict the trial effects in either experiment. Trial effects on postural sway in the context of suprapostural tasks have been reported by Pagulayan et al. (2001), who also did not predict them. These trial effects may be related to an effect observed by Stoffregen et al. (2000), who asked participants to shift their attention from a nearby target to a more distant target (or vice versa) in the middle of a trial. They found that sway changed during trials as a function of fixation distance; sway variability was reduced during fixation of nearby targets, relative to sway during fixation of more distant targets. The postural change appeared to be functional in that the impact on gaze of a given motion of the body scales negatively with the distance of fixated targets (for detailed discussion, see Stoffregen et al., 2000; Stoffregen et al., 1999). We do not claim that the trial effects observed in this study have a functional relation to visual performance. However, the robust trial effects observed in this study suggest that it may be useful, in future research, to analyze for possible trial effects.

GENERAL DISCUSSION

In two experiments we found that postural motion of the body was reduced when participants were instructed to shift their gaze to follow a moving target, relative to body sway during fixation of stationary targets. Eye movements made when the eyes were closed had no effect on motion of the torso; thus, the influence of eye movements on torso motion appeared to be functionally related to visual performance. These are the major findings of this study and they provide support for the

general hypothesis that body sway can be controlled, in part, so as to facilitate the achievement of suprapostural task goals. In addition, the angular displacement of visual targets was small enough so that required shifts in gaze could be accomplished without supporting head movements, and analysis of data on head motion confirmed that the head did not rotate differentially during viewing of moving and stationary targets. We discuss these results following.

Reduced Sway During Eye Movements

In this study, postural motion of the torso (and, in several cases, of the head) was reduced during visually guided eye movements relative to sway during fixation of a stationary target. Across two experiments and several manipulations, we never found an increase in sway during eye movements. Woollacott and Shumway-Cook (2002) argued that posture is not controlled in an automatic or reflexive manner. Our findings are compatible with their position. However, our findings do not fit comfortably with the most widely accepted interpretation of relations between the control of posture and suprapostural tasks. Many researchers have assumed that the control of posture relies on central cognitive processing resources (Dault et al., 2001; Lajoie et al., 1993; Maylor & Wing, 1996; White et al., 1980; Woollacott & Shumway-Cook, 2002; Yardley et al., 1999). An implication of this view is that the combination of postural control with simultaneous suprapostural tasks should produce competition for these central resources. Presumably, such a view leads to an interpretation of our experiments as combining a postural control task with an eye movement task, so that the two tasks would compete for central processing resources. Precisely this interpretation has been offered for a very similar situation studied by Hunter and Hoffman (2001). The competitive, dual-task view makes clear predictions about such situations. If the combined central processing demand of the two tasks exceeds the central processing resources that are available, then there should be a performance decrement in one or both of the combined tasks. If the combined central processing demand of the two tasks does not require more central processing resources than are available, then performance of the two tasks should be unaffected by the combination. This view has no apparent basis for predicting the result obtained in each of our experiments, in which postural sway was reduced when participants looked at a moving target, relative to sway during stationary fixation.

Our results also directly oppose predictions made by the saccadic suppression hypothesis (Oblak et al., 1985; White et al., 1980). Saccades may entail the suppression of visual information pickup, but any resulting loss of information about body sway clearly does not lead to an increase in postural motion.

The reduction in body sway while viewing a moving target is compatible with a different view of relations between postural control and suprapostural activity (Riccio & Stoffregen, 1988). In general, we do not view postural control as being in competition for central processing resources with concurrent suprapostural activi-

ties. This is because, for many activities, performance of suprapostural tasks may be influenced by postural motion. Because postural motion can influence the performance of suprapostural tasks, functional integration of postural control with suprapostural activity would be adaptive. In such circumstances, postural control would serve a dual function; on one hand, to avoid falling, and on the other hand, to optimize performance of suprapostural tasks (e.g., Massion, 1992). When the risk of falling is slight, as is generally the case for healthy adults and was certainly the case in our experiments, facilitation of suprapostural performance may play a stronger role in the organization of postural control. This view leads to the prediction that body sway may be reduced when such reductions can facilitate suprapostural performance (or, conversely, sway may be increased when such increases can facilitate suprapostural performance). When we view targets that are in motion, the success of eye movements (i.e., the maintenance of visual targets within the fovea) may be compromised by excessive body sway (among other things). Thus, one way to facilitate the viewing of moving targets might be to reduce sway. On this basis, we can predict that sway should be reduced when we look at moving targets, relative to sway during fixation of stationary targets. The results of each of our experiments are compatible with this hypothesis.⁶

Interpretations similar to ours have been offered by previous researchers, but on an ad hoc basis to explain unexpected findings. Oblak et al. (1985) found a reduction in mean radius of sway during visually guided eye movements, which contradicted their prediction of an increase in body sway during eye movements. In interpreting their results they suggested "the most logical conclusion is that the oculomotor system requires stabilization of posture to be able to hit the target light" (Oblak et al., 1985, p. 125). Similarly, Hunter and Hoffman (2001, p. 46) based their study on the a priori hypothesis of dual task competition for central processing resources but in light of their findings suggested a very different post hoc explanation: "A secondary task may, in effect, constrain the amount of acceptable postural sway." These post hoc explanations were made on an ad hoc basis (that is, without any motivation beyond the data at hand). The effects observed in this study were predicted a priori, and the predictions were derived from an established body of theory and research (Oullier, Bardy, Stoffregen, & Bootsma, 2002; Riccio & Stoffregen, 1988; Stoffregen et al., 2000; Stoffregen et al., 1999).

⁶Newell, van Emmerik, Lee, and Sprague (1993) reported an experiment demonstrating that variability may not be an appropriate dependent variable to use in operationalizing the concept of postural stability. We agree with their argument that variability is a poor measure of postural stability, and we have not used it in this way. We have used positional variability as a metric for the amplitude of body sway without interpreting any particular sway amplitude as being more or less stable. In part, this study (together with that of Stoffregen et al., 1999, and Stoffregen et al., 2000) can be interpreted as supporting the conclusions of Newell et al. Consistent with the position of Newell et al., we have not used positional variability as a measure of postural stability. Indeed, our position is that no measure of postural behavior, by itself, can be used to measure postural stability. In our view, the stability of postural control can be assessed only in the context of constraints imposed by suprapostural tasks.

The results of this study, and those of Hunter and Hoffman, Kikukawa and Taguchi (1985), and Oblak et al., are consistent with the idea that eye movement control is not limited to the muscles that act on the eyes (e.g., Steinman et al., 1990), but can extend to muscles acting on the head and torso. The results are also consistent with J. J. Gibson's (1966) broader assertion that the entire body is part of the visual system. These results underline the fact that looking is an act; it is something that people do, rather than being merely a response to external stimulation. The act of looking (i.e., the stable control of the eyes relative to targets of interest) can be influenced by movements of a variety of body parts and, as indicated by our experiments, by movements of the entire body (see also Anderson et al., 2001).

Postural Stabilization of Visually Guided Eye Movements

The second major finding of our study is that eye movements did not lead to changes in body sway when the eyes were closed. This finding indicates that body sway was modulated to support visual performance, and not to support ocular control, *per se*. Presumably, eye movements require some level of effort whether the eyes are open or closed. Whether the same amount of effort would be needed for these two tasks is unclear. On one hand, it might be argued that visually guided eye movements require greater effort because the viewer must search out, pick up, and use information about the orientation of the eyes relative to the external environment, and because even minor errors in eye movements can lead to substantial degradation in visual performance. On the other hand, it might be argued that greater effort would be needed to move the eyes during eye closure because of the novelty of this task. Theories of automatic processing generally argue that tasks require more cognitive resources when they are novel than when they are well practiced (e.g., Kahneman, 1973). It is not clear how to determine, *a priori*, whether such theories would predict that more resources would be required to move the eyes when they were open or when they were closed. However, we might evaluate part of the argument by giving participants extensive training at eyes-closed eye movements. Practice should reduce the effort required for this type of eye movement. If the dual-task competition view were correct, there should be a decrease in body sway as participants became more practiced at eyes-closed eye movements. We would predict that this change would not occur. On the contrary, with long practice we would expect to see the effect of eyes-closed eye movements on head motion (the reduction in head movements during eyes-closed eye movements relative to head movements during stationary eye closure; Experiment 1) disappear as participants became more skilled at moving the eyes independent of body sway.

We have suggested that reductions in sway variability may have facilitated shifts in gaze in our experiments. We do not claim, however, that gaze stabilization would always imply reductions in sway. In some cases visual performance might be facilitated by increasing the overall magnitude of sway, provided that the increased mo-

tion served to facilitate gaze. One recent study is consistent with this idea. Glasauer, Schneider, Jahn, Strupp, and Brandt (2005) measured sway and eye movements while standing participants looked at moving and stationary targets. Target motion consisted of sinusoidal horizontal oscillations at 0.33 Hz, 12° amplitude. Stance was heel to toe. The results revealed an increase in RMS sway in the ML axis when moving targets were presented. This might be interpreted as conflicting with our finding that sway variability tended to be reduced when participants looked at moving targets, but such an interpretation can be questioned. Glasauer et al. did not evaluate the hypothesis that ML postural oscillations may have become coupled with the horizontal smooth pursuit movements used to track the visual targets. However, they presented median data for eye movements and for ML sway that strongly suggest that coupling occurred. Coupling of ML sway with horizontal eye movements may have been functional, that is, the coupling may have facilitated performance in the visual tracking task. Such an effect would be consistent with our general hypotheses. It would be interesting to examine links between gaze and postural control while varying stance (e.g., feet side by side vs. heel to toe) and while varying the type of eye movements required (saccades vs. smooth pursuit).

The Role of Cognition

In our experiments, was posture influenced by task-related constraints on the visual system, or by variations in the cognitive difficulty of tasks? The latter possibility might seem credible for tasks that require an obvious cognitive component, such as mental arithmetic (e.g., Yardley et al., 1999), or searching a text for target letters (e.g., Stoffregen et al., 2000), but it is less credible for the simple eye movements required in our experiments. With such simple eye movements it seems to us more reasonable to conclude that posture was influenced by constraints related to the visual tasks. The issue could be tested by varying the mental workload of visual tasks independently of their "ocular workload," that is, by independently varying levels of cognitive effort and ocular stability required for the performance of visual tasks.

Shifting Gaze Without Head Rotation

Our measurements of eye position confirm that participants moved their eyes, and that the amplitude of eye movements matched the amplitude of target displacement. The match between eye movement amplitude and target displacement fits well with our analysis of head rotation around the vertical axis, which showed that head rotation was not influenced by movement or stasis of the targets. Thus, we conclude not only that the postural effects observed in this study were related to movements of the eyes, but that they were not related to rotation of the head. We do not suggest that head movements are irrelevant to the influence of postural control of dynamic gaze. We eliminated head rotation solely because it would tend to alter motion of the torso, which would complicate our effort to understand rela-

tions between eye movements and stance. When gaze shifts are large enough to elicit head rotation, we would expect that motion of the torso, head, and eyes are integrated to optimize visual performance.

CONCLUSION

Woollacott and Shumway-Cook (2002), defined postural control as "the control of the body's position in space for the purposes of balance and orientation" (p. 1). Presumably, by *orientation* Woollacott and Shumway-Cook referred to the orientation of the body. Our research suggests that this definition may not fully capture the functional value of postural control. Our results suggest that one function of postural control is to stabilize the visual system so as to facilitate the accuracy of small changes in the direction of gaze. Beyond this our results, together with those of Stoffregen et al. (2000) and Stoffregen et al. (1999), suggest that there may be movement signatures of the difficulty of different suprapostural tasks.

We asked participants to move their eyes at constant amplitude and frequency. It would be interesting to vary the amplitude and/or frequency of eye movements in the context of postural sway. The integration of eye movements and body sway observed in this study might be influenced by the amplitude of eye movements (e.g., a negative relation between the amplitude of eye movements and the amplitude of sway), or by eye movement frequency (e.g., a negative relation between the frequency of eye movements and the amplitude of sway). Another area for future research concerns the dynamics of body sway and eye movements. Body sway is periodic motion and in our experiments eye movements were also periodic. Body sway is known to have characteristics of dynamical systems, such as stable coordination modes, sudden transitions between modes, critical slowing down, and hysteresis (e.g., Bardy, Marin, Stoffregen, & Bootsma, 1999; Bardy, Oullier, Bootsma, & Stoffregen, 2002; Oullier et al., 2002). When following the motion of oscillating targets, ocular control may also function as a dynamical system, in which case we might expect to observe coupling of the dynamics of the postural and ocular systems (e.g., phase locking). This study suggests that any dynamical coupling of these systems should be functional, that is, it should facilitate visual performance. Finally, our experiments were concerned exclusively with shifts in gaze achieved using saccadic eye movements. Future research should evaluate the hypothesis that body sway can be modulated to facilitate the performance of continuous changes in the direction of gaze (i.e., tracking eye movements).

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Sound Source Perception in a Two-Dimensional Setting: Comparison of Action and Nonaction-Based Response Tasks

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Laboratory investigations into auditory spatial perception predominantly involve the manipulation of the sound source along a single dimension. Nonetheless, sound-producing objects in natural settings exist and vary within a multidimensional space. Moreover, laboratory investigations in auditory perception typically involve participants performing a task they do not commonly perform in everyday situations (e.g., magnitude estimation task). This study served two purposes. First, the ability of observers to judge sound source position across two dimensions was determined. Second, a comparison was made between magnitude estimation and action-based metrics. The results revealed that perceptual judgments were notably more accurate when participants walked to the sound source than when target location was verbally reported using a combination of feet, inches, and degrees. The findings of this study lend additional support to Gibson's (1979/1986) notion that perception and action are mutual or coupled terms.

Under everyday circumstances, perceiving-acting organisms are exposed to numerous sound-producing objects that differ greatly in their position or location within three-dimensional space. Sounds vary in distance from the point of observation. Sounds also vary in azimuth (i.e., the angle between the point of observation and the sound source relative to the median plane) and elevation or altitude (i.e., the angle or height of a sound source relative to the ground plane). Yet only a small number of studies have examined the ability of observers to locate sounds that varied in azimuth as well as elevation (e.g., Makous & Middlebrooks, 1990;

Middlebrooks, 1992; Oldfield & Parker, 1984; Wightman & Kistler, 1989). Likewise, only a few studies have examined perception across variations in both sound source azimuth and sound source distance (e.g., Loomis, Klatzky, Philbeck, & Golledge, 1998; Loomis, Lippa, Klatzky, & Golledge, 2002; Speigle & Loomis, 1993; Wanet & Veraart, 1985).

In those instances when source azimuth and distance were varied, observers were not equally capable of judging target distance and target location. For example, in a study by Loomis et al. (2002; see also Speigle & Loomis, 1993), participants were required to walk to the source of a sound signal that ranged in distance from approximately 2 to 5 m and varied in azimuth from -90° to $+90^\circ$ (0° being directly ahead). Whereas judgments of target azimuth were nearly veridical, judgments of source distance were consistently imprecise. More specifically, participants tended to overestimate nearby targets and underestimate distant ones. This tendency of observers to accurately gauge target azimuth but inaccurately gauge target distance has also been found when the target was within the reach of the participant (Wanet & Veraart, 1985) as well as when the target was at greater distances, 5 to 15 m (Loomis et al., 1998).

Traditionally, investigations into auditory perception have required observers to provide a verbal report of the location of the auditory target. It has frequently been the case that participants have been required to report target location in degrees (e.g., Begault & Wenzel, 1993; Endsley & Rosiles, 1995) or meters, centimeters, feet, or inches (e.g., Butler, Levy, & Neff, 1980; Holt & Thurlow, 1969; Little, Mershon, & Cox, 1992; Mershon, Ballenger, Little, McMurtry, & Buchanan, 1989; Mershon & Bowers, 1979; Mershon & King, 1975; Zahorik & Wightman, 2001). Elsewhere, participants have been required to judge sound position relative to a visually evident object or reference point (e.g., Bronkhorst & Houtgast, 1999; Cochran, Throop, & Simpson, 1968; Simpson & Stanton, 1973). It has also been customary for participants to provide a verbal report as to which of a number of visually apparent loudspeakers was the source of the sound (e.g., Belendiuk & Butler, 1975; Butler, Humanski, & Musicant, 1990; Coleman, 1962; Gardner, 1969) or which of a number of sounds was closer or more distant (e.g., Ashmead, LeRoy, & Odom, 1990; Barencutt & Pfeffer, 1998). Undoubtedly, response measures such as these allow for a precise evaluation of the accuracy of observers' perceptual capabilities. Nonetheless, such metrics do not address the perceptual problems and tasks faced by perceiving-acting organisms under naturalistic circumstances. Rarely is it the case that an observer will verbally report the distance of a sound-producing object or judge whether the sound was closer or more distant than some other object.

Although verbal reports are commonly employed in the study of auditory perception, a number of studies have made use of an action-based metric. Ashmead, Davis, and Northington (1995), for example, examined the ability of observers to judge the location of a sound source that varied in distance from 5 to 19 m from the point of observation. The task of their participants was to walk to the perceived origin of the sound. In short, perceptions of distance were nearly veridical. With regard to sound

sources proximate to the point of observation, Rosenblum, Wuestefeld, and Anderson (1996) required participants to report whether a sound source was sufficiently close that it could be grasped. Judgments of reaching were limited to maximal arm extension when target distance ranged from 38 to 110 cm, or to maximal arm extension plus bending at the hip when target distance ranged from 78 to 150 cm. The findings revealed that targets at a distance of less than 0.92 times the observer's arm length were deemed reachable, whereas targets more distant than 0.92 times observer arm length were deemed unreachable. Additional studies have likewise found that auditory perceptual judgments tend to be highly accurate when participants are allowed to use an action-based metric (e.g., Litovsky & Clifton, 1992; Russell & Turvey, 1999).

When body-neutral and body-referential perceptual responses have been directly compared, the results suggest that the latter yields superior perceptual judgments of sound source location. Haber, Haber, Penningroth, Novak, and Radgowski (1993) required participants to judge sound source azimuth using nine pointing methods. Three of the report measures were body referential (point with nose, chest, or finger). Two involved an extension of the body (pointing with a short stick or long cane). Three involved an external instrument (two involved a dial, one involved drawing a line representative of the angle of the target). The final method required participants to verbally report source position in terms of the hour hand of a clock (with 12 o'clock being directly ahead). Their findings revealed that judgments were significantly more accurate and more consistent when the response task involved a body-referential metric (i.e., the first five response measures). Perceptual error, on average, was 7.6° for the body-referential metrics and 12.7° for the body-neutral metrics, a difference of approximately 67%. Loomis et al. (1998) likewise found observers to be more consistent in their judgments of target distance when they walked to the sound source than when they verbally reported its distance.

The purpose of this study was twofold. First, the ability of sighted but blindfolded observers to locate a nearby sound source was examined in light of variations in target distance and azimuth. Although such variations have been performed previously, this study sought to extend our understanding of auditory perception across multiple dimensions by using a range of target distances and azimuths intermediate to those used previously. The second purpose of this study was to determine the extent to which perceptual judgments differed as a function of the response task. Although previous studies have compared various response tasks, no known study has yet to do so when a sound source is varied in multiple dimensions. Differences between body-centered and body-neutral perceptual responses, for example, may only be applicable to sound sources varying within a single dimension. In this study participants either performed a magnitude estimation task or walked to the perceived location of the sound source. Assuming the findings of this study are comparable to previous investigations, participants who actively responded to the sound should be perceptually more accurate than those who verbally responded.

METHOD

Participants

A total of 18 undergraduates enrolled in an introductory psychology course participated in partial fulfillment of a course requirement. An equal number of participants were assigned to the two conditions (described later). All participants reported having normal, unaided hearing. None had previously participated in an auditory perception experiment.

Materials

The sound stimulus consisted of three notes of a 0.7 kHz tone, with a note duration of 330 ms and an internote interval of 400 ms. Signal amplitude measured 10 cm from the loudspeaker was 74 dB. The stimulus was generated digitally using the software program Cool Edit 2000. A Macintosh iBook computer and external loudspeaker (Model AD-800, Labtec, Las Vegas, Nevada) were used to broadcast the sound signal. The loudspeaker was positioned on top of a silently moving, swinging support arm and had a height of 90 cm relative to the floor. The support arm pivoted about a point 1.85 m to the right of the observer and had a range of approximately 180°. Figure 1 contains a schematic of the experimental arrangement.

The experimental room was reverberant (i.e., echoic)¹ and measured 2.93 m in width, 4.15 m in length, and 3.08 m in height. The walls and ceiling were composed of standard drywall material (absorption coefficient = 0.20) and the floor was covered with linoleum tile (absorption coefficient = 0.03). Reverberation time (RT₆₀) for the room was calculated to be 0.52 sec.

During those trials that required the participant to walk to the location of the sound source, the position of the observer was determined using a sonic measuring device (Zircon, model DM-S50). The device has a reported accuracy of 99.5% according to the manufacturer. An equivalent degree of accuracy was replicated in the laboratory. Throughout the experiment, all participants wore a blindfold.

Design and Procedure

On arrival to the experimental room, informed consent was obtained and participants were randomly assigned to either the verbal or action condition. Once the participant was positioned at the starting location (see Figure 1), instructions were

¹An echoic setting was selected for three reasons. First, indirect or reverberant sound has been shown to be a significant source of information about the position of sound-producing objects. Second, the ability of observers to judge the position of a sound source that varied in two-dimensions in an echoic setting has not been previously explored. Third, observers typically encounter sounds in echoic settings. Thus, an echoic setting enhances the external and ecological validity of the study.

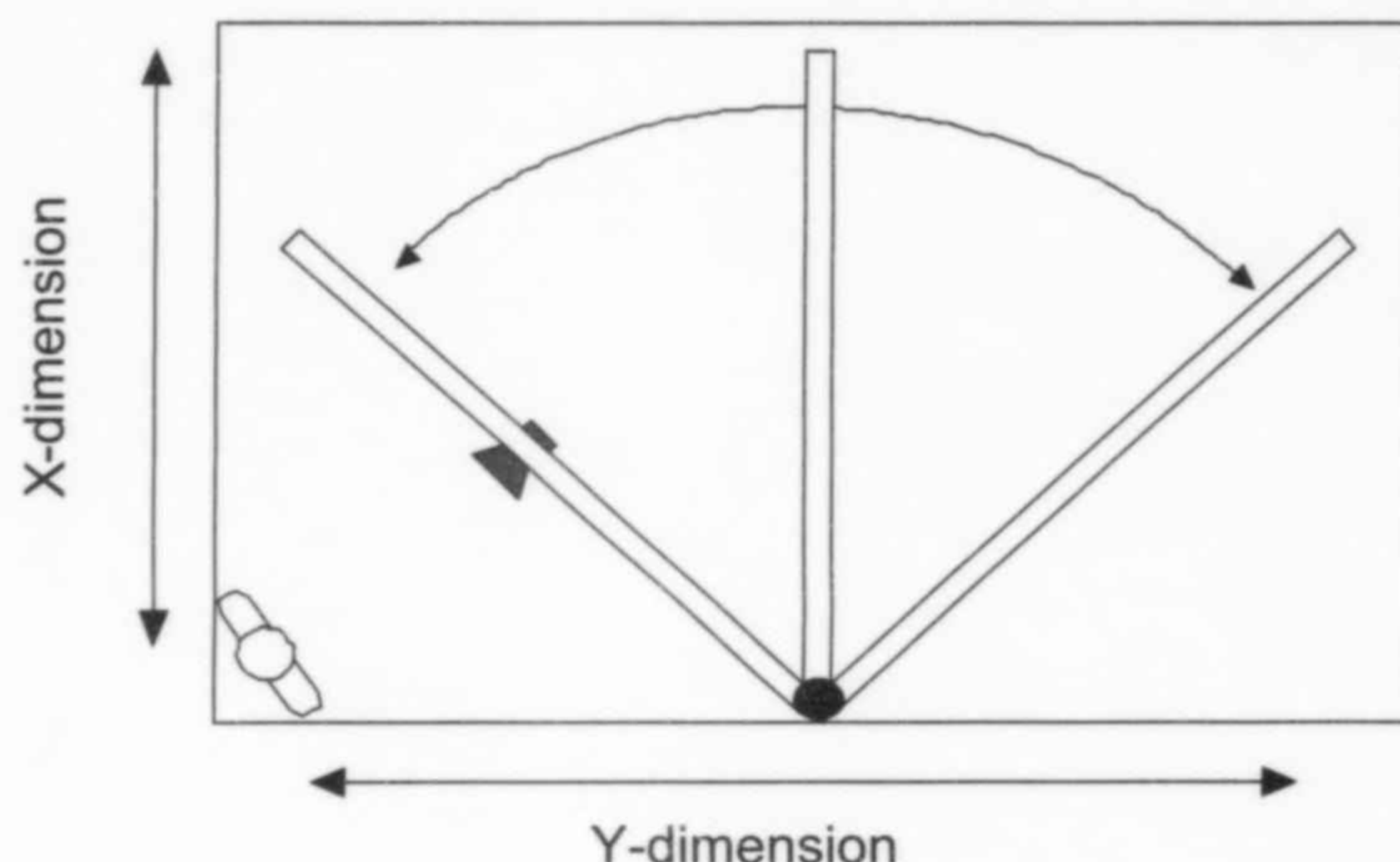


FIGURE 1 Schematic representation of the experimental arrangement used in this study, including the nine locations of the sound source.

given. For the verbal condition, participants were informed that their task was to verbally report the distance and azimuth of the auditory target relative to their location. Distance judgments were reported in feet and inches for the sake of familiarity with that metric, whereas azimuth was reported in degrees. Participants in the verbal condition were also informed that targets to the left of their midline were to be assigned a negative azimuthal value, and targets to their right were to be reported as positive values. Targets believed to be directly ahead (i.e., along the observer's midline) were assigned an azimuthal value of zero. For those individuals assigned to the action condition, participants were informed that, following the complete broadcast of the sound signal, their task was to walk to the origin of the sound signal. While the participant was in motion, the support arm and loudspeaker were manually relocated so as to prevent any collision that might have injured the participant and/or provided feedback. Once the participant had reached the final location, he or she was asked to remain fixed at that point while the position was calculated. The distances traveled in the X and Y dimensions (see Figure 1) were determined using the sonic measuring device. After the distances were recorded, the experimenter then guided the blindfolded participant back to the starting point. For all participants, the starting point was identical and participants were required to respond only after the sound signal was broadcast in its entirety. Furthermore, all participants were encouraged to be as accurate as possible in their responses. Once the instructions were given and any questions answered, the participant was blindfolded and the experiment began.

From the perspective of the participant, the sound source could exist at any of a large number of positions relative to the point of observation. However, each participant was exposed to only nine target locations (see Table 1). The choice of nine locations rested on the desire to vary source angle and distance as greatly as possible given the limitations of the experimental apparatus and the experimental set-

TABLE 1
The Angle^a and Distance^b for the Nine Sound Source
Locations Used in This Study (See Figure 1)

<i>Target Location</i>	<i>Angle</i>	<i>Distance</i>
1	17.70	1.59
2	-7.95	1.55
3	-20.72	1.75
4	19.36	1.83
5	0.49	2.14
6	-8.44	2.43
7	25.06	2.15
8	14.37	2.70
9	9.74	3.09

^aIn degrees. ^bIn meters.

ting. Each of the nine target locations was randomly presented four times each, thereby yielding a total of 36 trials. Target location and position were accomplished by the experimenter manually repositioning the loudspeaker along the support arm and/or by pivoting the supporting arm. The experiment lasted approximately 30 to 45 min. Neither feedback nor practice trials were provided. Participants remained blindfolded throughout the experiment.

RESULTS

To gain a clear understanding of observer perceptions, the accuracy of each participant's judgments was calculated for each trial separately in terms of both target azimuth and target distance. For those in the verbal condition, this was accomplished directly because distance and azimuth judgments were recorded in each trial. However, for those in the action condition, the distances the individual traveled in the X and Y dimension were used to calculate perceived angle and distance.

For all participants, the mean signed and absolute errors were calculated for both target distance and target azimuth. Signed error was calculated by taking the difference between the actual position of the sound source and its perceived position. Here, a positive signed error value reflected the tendency of participants to overestimate target distance or, with respect to azimuth, to perceive the target as being further from the midline than the sound source actually was. In contrast, a negative signed error score reflected the underestimation of target distance or the tendency to perceive the sound source as closer to the observer's midline than was

actually the case. The advantage of using signed error scores is that they reveal the extent to which participants underestimated or overestimated target location. One potential disadvantage to the use of signed error scores is that the combination of positive and negative values may provide a false impression of perceptual accuracy. For example, overestimating target angle by 12 degrees on one trial and underestimating it by 12 degrees on another would yield an average signed error value of zero.

Although it is merely possible that signed error scores may not precisely reflect observer performance, absolute error was calculated as well. Absolute error was calculated by determining the unsigned difference between actual and perceived sound source position. As with signed error, this was done for each trial and for each participant. The advantage of absolute error scores is that they reflect the overall accuracy of observer judgments. However, such scores fail to reveal the direction of that error. For this reason, signed and absolute error scores were calculated for each participant and for each trial. Following that, the mean performance of each participant (i.e., averaged across the four exposures) for each sound source position was determined and analyzed.

In terms of the perception of sound source angle, a 2 (Condition) $\times$ 9 (Target Location) analysis of variance (ANOVA) performed on the mean participant performance signed error data revealed a significant main effect of observer condition, $F(1, 144) = 45.64, p < .0001$. Target angle tended to be underestimated by participants in the action condition ($M = -3.77^\circ$) and overestimated by those in the verbal condition ($M = 4.45^\circ$). The accuracy with which participants judged target angle was found to vary with target location, $F(8, 144) = 5.46, p < .0001$. Essentially, target angle was overestimated when the target was to the far right of the participant (i.e., target locations 1, 4, and 7) and underestimated otherwise. A Tukey test ($p = .05$) revealed perceptual error for location 1 ($M = 8.11^\circ$) to be higher and significantly different from all other locations, with the exception of locations 2, 4, and 7. It was also revealed that the perceptual error associated with location 9 ($M = -4.58^\circ$) was significantly different from that of locations 4 and 7 ($M_s = 3.69^\circ$ and 3.50° , respectively). No other pairwise comparisons reached significance. Finally, the results of the ANOVA showed that perceptual error varied as a function of source location and participant condition, $F(8, 144) = 6.22, p < .0001$; see Figure 2.

A 2 (Condition) $\times$ 9 (Target Location) ANOVA on the perceived angle absolute error data yielded a significant main effect of condition, $F(1, 144) = 108.73, p < .0001$. Generally speaking, individuals in the action condition judged target angle more accurately than those in the verbal condition ($M_s = 6.04^\circ$ and 12.55° , respectively). With regard to the main effect of target position, the findings showed that perceptual error increased as the sound source deviated from the midline of the observer, $F(8, 144) = 9.84, p < .0001$. Interestingly, perceptual error was greatest for location 1, the nearest sound source location ($M = 15.60^\circ$). A Tukey test (p set at .05) revealed that location 1 was judged significantly less accurately than all other locations. Significant differences also existed between locations 4 and 5 (M_s

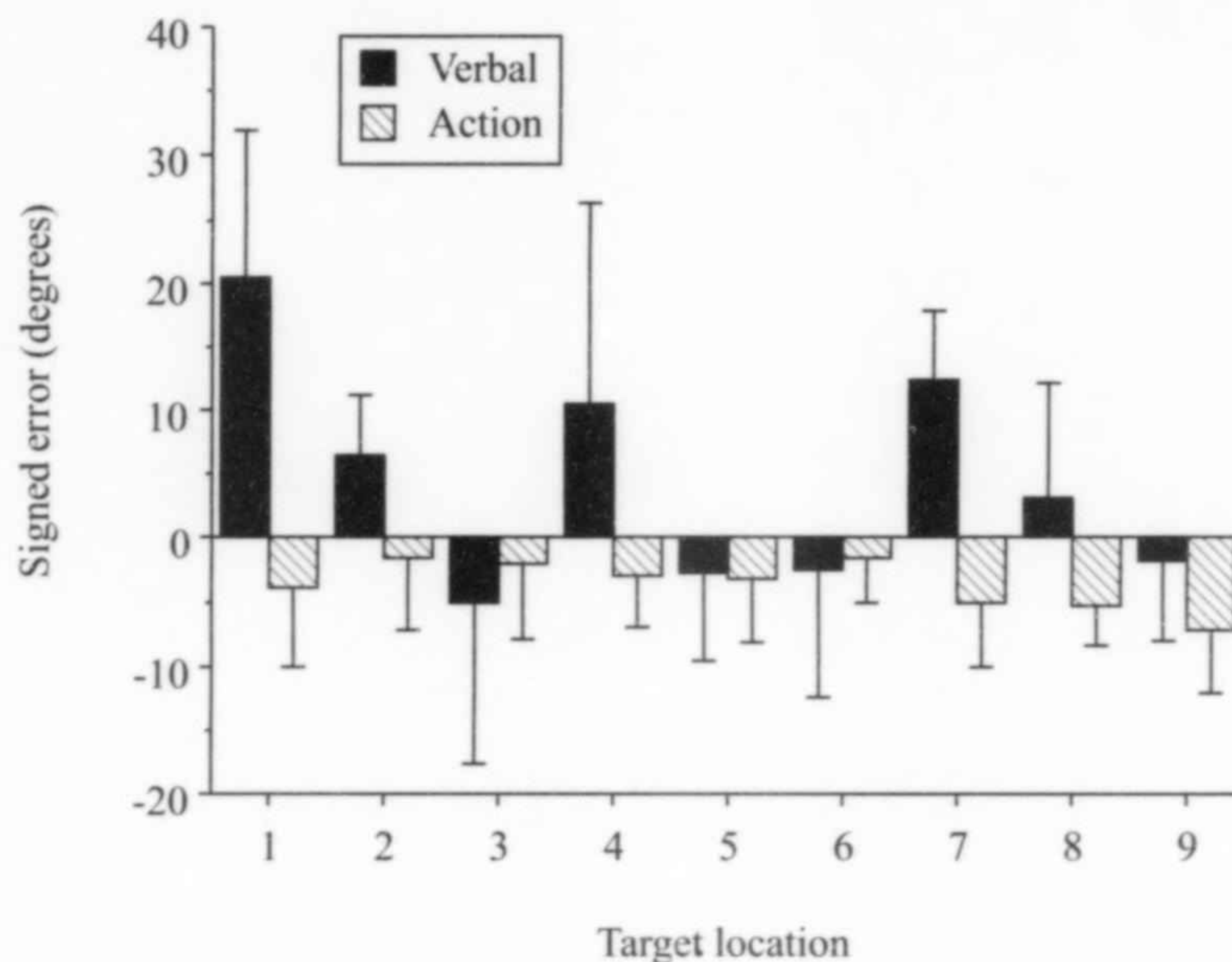


FIGURE 2 Signed error of perceived angle as a function of participant condition and target location.

= 11.46° and 5.98°, respectively), 3 and 5 ($M_s = 10.28^\circ$ and 5.98° , respectively), and 4 and 2 ($M_s = 11.46^\circ$ and 6.82° , respectively). The two-way interaction was also found to be significant, $F(8, 144) = 11.28, p < .0001$; see Figure 3. For participants in the action condition, perceptual judgments erred by less than seven degrees for all but location 9 ($M = 9.23^\circ$). For those in the verbal condition, perceptual error appeared to increase as the sound source deviated from the observer's midline.

To ascertain the extent to which target distance was overestimated or underestimated, a 2 (Condition) $\times$ 9 (Target Location) ANOVA was conducted on the signed error data. The main effect of condition was found to be significant, $F(1, 144) = 306.40, p < .0001$. Target distance was overestimated by participants in the action condition ($M = 0.32$ m) and underestimated by those in the verbal condition ($M = -1.06$ m). Perceptual error was also found to be marginally affected by variations in target location, $F(8, 144) = 1.94, p = .06$. A Tukey test (p set at 0.05) revealed that there existed a significant difference in the error of distance judgments between locations 1 and 7 ($M_s = -0.63$ and -0.04 meters, respectively). All other pairwise comparisons were not significant. The interaction between condition and source location failed to approach significance, $p > .30$. As can be seen in Figure 4, distance judgments were consistently overestimated by those in the action condition and consistently underestimated by those in the verbal condition.

To determine the magnitude of error in distance perception, a 2 (Condition) $\times$ 9 (Target Location) ANOVA on the absolute error data for perceived distance was performed. A significant main effect of condition was obtained, $F(1, 144) = 71.47$,

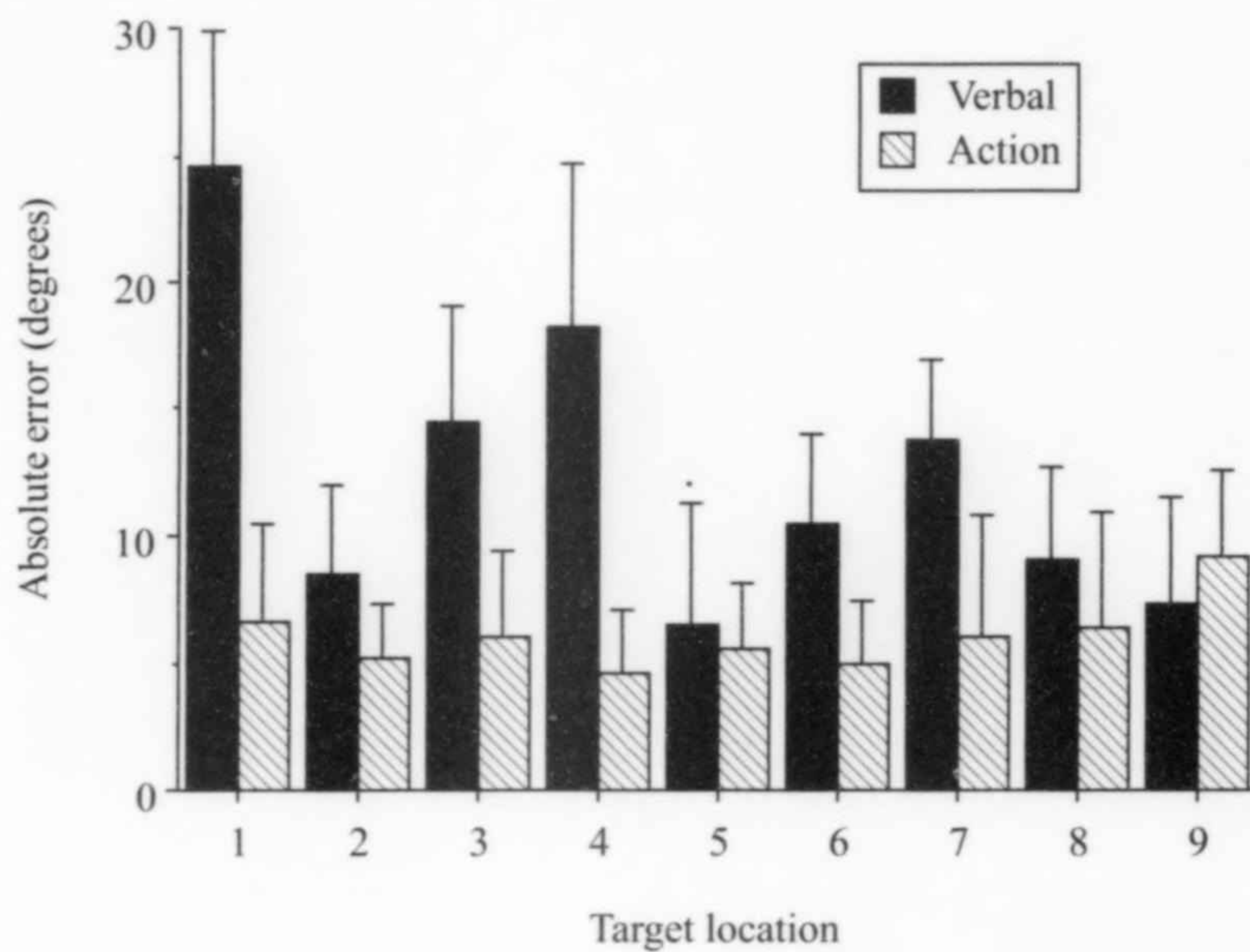


FIGURE 3 Perceived (absolute) error of target angle in relation to participant condition and target location.

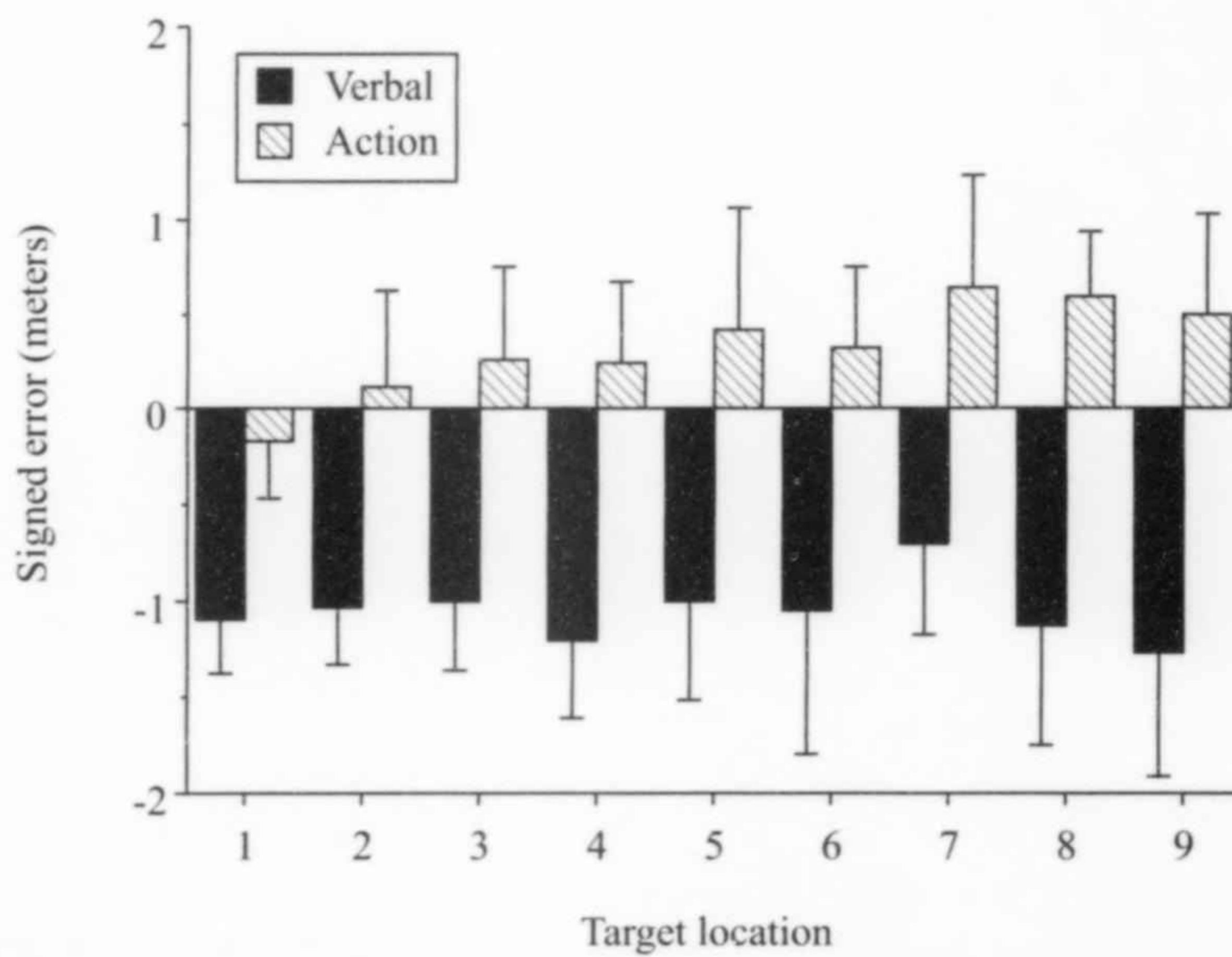


FIGURE 4 Signed error of perceived distance as a function of participant condition and target location.

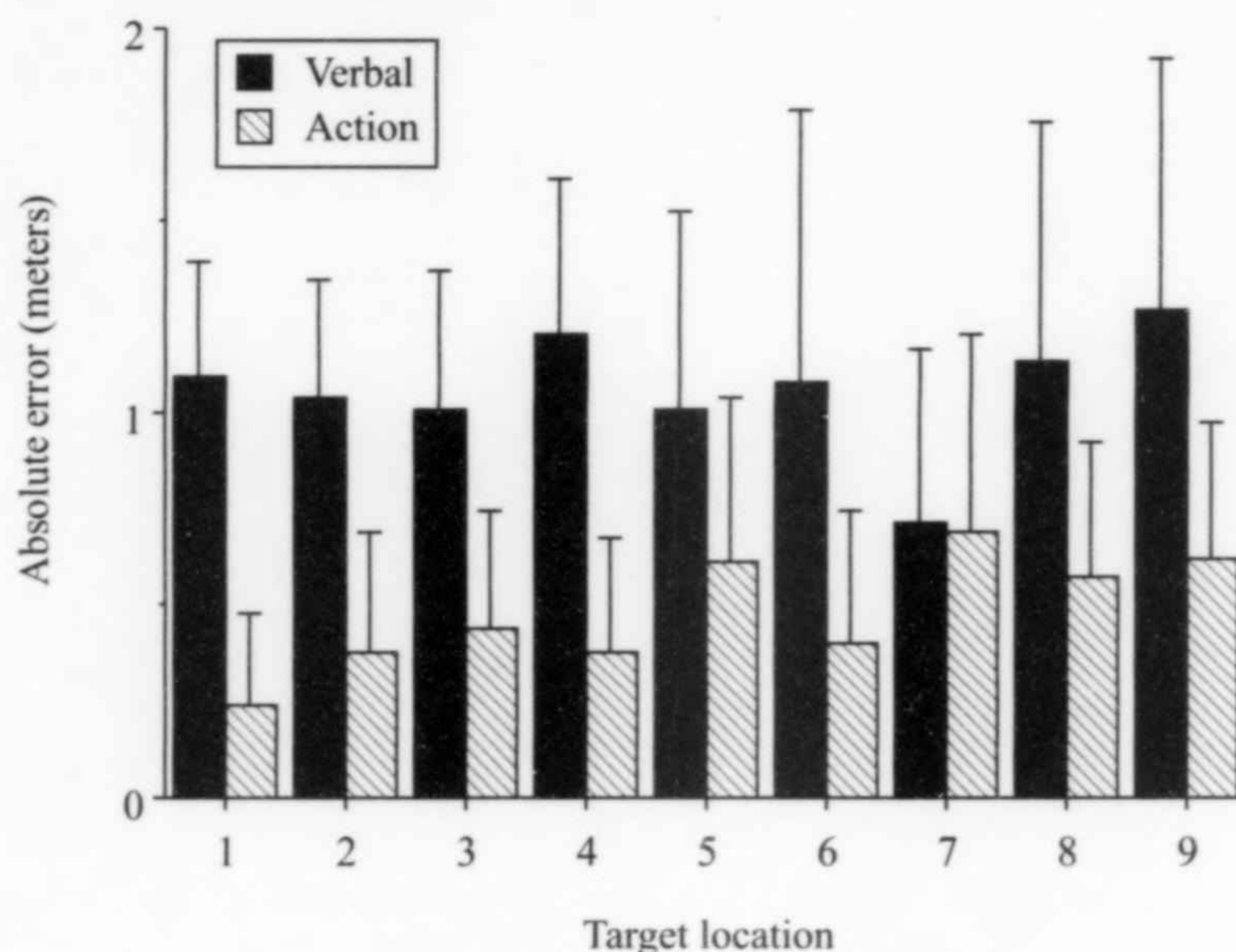


FIGURE 5 Absolute error in the perception of target distance in relation to the location of the sound source and participant response task.

$p < .0001$. Perceptual error by those in the verbal condition was found to be more than twice as large as those in the action condition ($M_s = 1.06$ and 0.48 , respectively). Neither the main effect of sound source location nor the two-way interaction were significant ($p_s > .15$). Despite the extent of the difference in perceptual error between conditions, the level of performance was fairly consistent across variations in sound source location (see Figure 5).

DISCUSSION

Previous investigations involving the manipulation of source distance and azimuth have found judgments of sound source azimuth to become less accurate as the sound source increasingly deviated from the observer's midline (e.g., Loomis et al., 1998; Loomis et al., 2002; Speigle & Loomis, 1993).² Those same studies also found the accuracy of azimuth judgments to be unaffected by variations in observer-source distance. With regard to this study, participants in the action condi-

²Comparison of the findings of this study with those of similar, prior investigations is difficult for several reasons. First, the few studies that have examined auditory perception across variations in target distance and azimuth have used target distances, azimuths, sounds, and settings notably different from that used in this study. Thus, caution should be taken in the comparisons of findings. Second, prior investigations did not report mean participant performance. Instead, the results were graphically represented and only the significance values, slopes, and intercepts of linear functions were reported in the text.

tion, the condition similar to that used in prior investigations, judged target azimuth with a degree of accuracy unaffected by either a change in actual target azimuth or observer-source distance. Although numerous methodological differences between this study and prior investigations preclude an explanation about the partial disparity in results, the findings of this study suggest that the angular position of a nearby sound-producing object can be judged with a relatively high degree of accuracy despite notable variations in target azimuth and distance.

Previous studies involving the manipulation of both source distance and azimuth have found judgments of sound source distance to be inexact. It has been shown, for example, that perceptual accuracy decreases with an increase in observer-source distance (e.g., Loomis et al., 1998; Loomis et al., 2002). Observers have also been found to overestimate nearby targets and underestimate more distant ones (e.g., Loomis et al., 2002; Speigle & Loomis, 1993). Common to those studies was the lack of an effect of target angle. That is, the accuracy of distance judgments remained unchanged despite variations in target azimuth. The findings of this study are in accordance with the findings of previous investigations. More specifically, the accuracy of distance judgments was found to decrease with an increase in observer-source distance. Perceptual judgments were also found to be equally accurate regardless of whether the sound source was aligned with the observer's midline or not. The fact that perceptual judgments were least accurate when the sound source was distant may be a reflection of observer hesitancy. As can be imagined, observers may have been hesitant about walking great distances while blindfolded for fear of colliding with one of the walls of the experimental room. Although support does exist for this notion (e.g., Thomson, 1983), future research is undoubtedly required to substantiate this claim.

The primary purpose of this study was to determine the extent to which judgments of sound source position were affected by the response task of the observer. In short, perceptual reports of target azimuth and target distance were significantly less accurate when a verbal report was provided than when observers actively responded. More to the point, perceptual error was approximately twice as great when participants performed a magnitude estimation task than when they simply walked to the perceived origin of the sound signal. The existence of such large disparities in performance between conditions suggests that it may be advantageous to allow observers to perform an action-based response rather than a magnitude estimation task. In light of the findings of this study, and considering that magnitude estimation tasks are frequently used in investigations into auditory spatial perception, it may be prudent to reconsider the way in which perception is investigated in the laboratory.

The results of this study further suggest that individuals in the verbal condition were affected to a greater degree by variations in target azimuth, and those in the assigned condition were affected by changes in target distance. For those in the verbal condition, targets located to the far right of the observer were overestimated by 10° or more; targets to the left were underestimated by 5° or less. Targets located

along the observer's midline were overestimated or underestimated by nearly 4° . In contrast, those assigned to the action condition underestimated target angle by approximately 5° , irrespective of the actual location of the sound source. With regard to the perception of target distance, participants in the action condition were able to accurately judge nearby targets. However, an increase in observer-source distance tended to result in a greater degree of overestimation. In contrast, those who provided verbal reports tended to consistently underestimate target distance by approximately 1 m irrespective of actual target distance and location.

It is clear from the findings of this study that perceptions of sound source location are influenced by the way observers report the position of the auditory target. In this respect, the findings of this study are in accordance with those of previous investigations (e.g., Haber et al., 1993; Litovsky & Clifton, 1992; Montello, Richardson, Hegarty, & Provenza, 1999). More important, the findings of this study further our understanding of the ability of sighted but blindfolded observers to locate objects by sound. As stated in the introduction, under everyday circumstances, targets of perception exist and vary along multiple dimensions. Despite this commonsense observation, the vast majority of investigations into auditory spatial perception have restricted their study to a single dimension. The few studies that have examined perception across variations in source azimuth and distance have involved targets at distances of several meters. It should be noted that the achievement of those large distances, in combination with the desire to minimize sound reverberation, required the use of wide, open spaces. Such settings contrast notably with the settings typically inhabited by human observers. It is commonly the case that humans, and nonhumans on occasion, perceive and act within limited regions. Occupying a limited region restricts the distance of a perceptual target and results in a nontrivial increase in sound reverberation. As a result of this study, what is now known is that observers are capable of accurately judging the position of a nearby sound source that varies in azimuth and distance, assuming they are permitted to act. If, however, observers are required to perform a magnitude estimation task, as is commonly done in psychophysical experiments, it can be expected that observer judgments of target distance and target azimuth will be exceedingly inaccurate. In sum, this study has furthered our understanding of the ability of observers to locate sound-producing objects that vary in multiple dimensions. We now have a first glance at the ability of observers to judge the combination of source distance and azimuth within a limited space. The findings of this study have also revealed, for the first time, that those perceptual judgments are a reflection of the way observers are permitted to respond.

According to Gibson (1979/1986), perception and action should be considered mutual or reciprocal terms. By mutual or reciprocal, it is meant that consideration of one mandates consideration of the other. "Perception serves behavior, and behavior is controlled by perception" (Gibson, 1979/1986, p. 223). It is believed, for example, that an active organism can better accomplish a perceptual task than can a stationary organism. Such notions are highly applicable to audi-

tory spatial judgments, particularly those that occur in naturalistic settings. To determine the origin of a sound-producing object, one could simply provide a verbal estimate, as is done frequently in auditory perception studies. Under everyday circumstances, however, both human and nonhuman organisms solve this task by acting. To become spatially coincident with a sound-producing object, an observer must first know the direction of the sound. Source direction can be easily discerned by altering the position of the head so as to minimize the differences in sound reaching the two ears (i.e., minimize interaural differences). Having done so, spatial coincidence can be accomplished by moving in such a way that the intensity of the sound increases. Coincidence exists when signal intensity at the point of observation is at a maximum level and when no interaural differences exist. If a particular movement yields an increase in interaural differences or a reduction in signal intensity, then the direction of movement need only be undone.

Gibson (1979/1986) further argued that a stationary point of observation should be considered a "limiting case" or the "null case" (p. 72). Organisms, in natural settings, are consistently and frequently acting. For this reason, it is believed that restrictions on observer movement are likely to limit the information that can be detected, which, in turn, will limit or impair perceptual judgments. With respect to auditory spatial perception, empirical support exists for this notion. Ashmead et al. (1995; see also Speigle & Loomis, 1993) found that judgments of target distance were less accurate for stationary observers than for observers who were walking during sound broadcast. However, it should be noted that both of these studies were conducted in outdoor settings. The limited size of most indoor settings, such as the one used in this study, precludes the use of translating observers. If observers in this study were permitted to walk during sound broadcast, the number and range of possible sound source locations would have been dramatically reduced and would have provided a false impression of perceptual accuracy. It is also worth noting that limitations on body posture were not imposed on observers while at the starting point. That is, although observers were not allowed to move from the starting point during sound broadcast, pivoting of the body, torso, and head were permitted. Changes in body stance (but not location) and head position have been found to be sufficient to affect perceptual judgments (e.g., Mark, Balliett, Craver, Douglas, & Fox, 1990) and may have influenced the judgments of those in this study. Obviously, future research is needed to determine the extent to which such movements affect auditory spatial perception.

From a Gibsonian, ecological perspective, magnitude estimation judgments should be considered anomalous. Under everyday circumstances, observers rarely report the distance or elevation of a sound source in feet or inches. It is also highly unlikely that observers will report sound source position in degrees. The finding in this study of largely erroneous perceptual reports when participants were required to use such metrics should not be surprising from the ecological perspective. The fact that perceiving-acting organisms are better at judging the position of

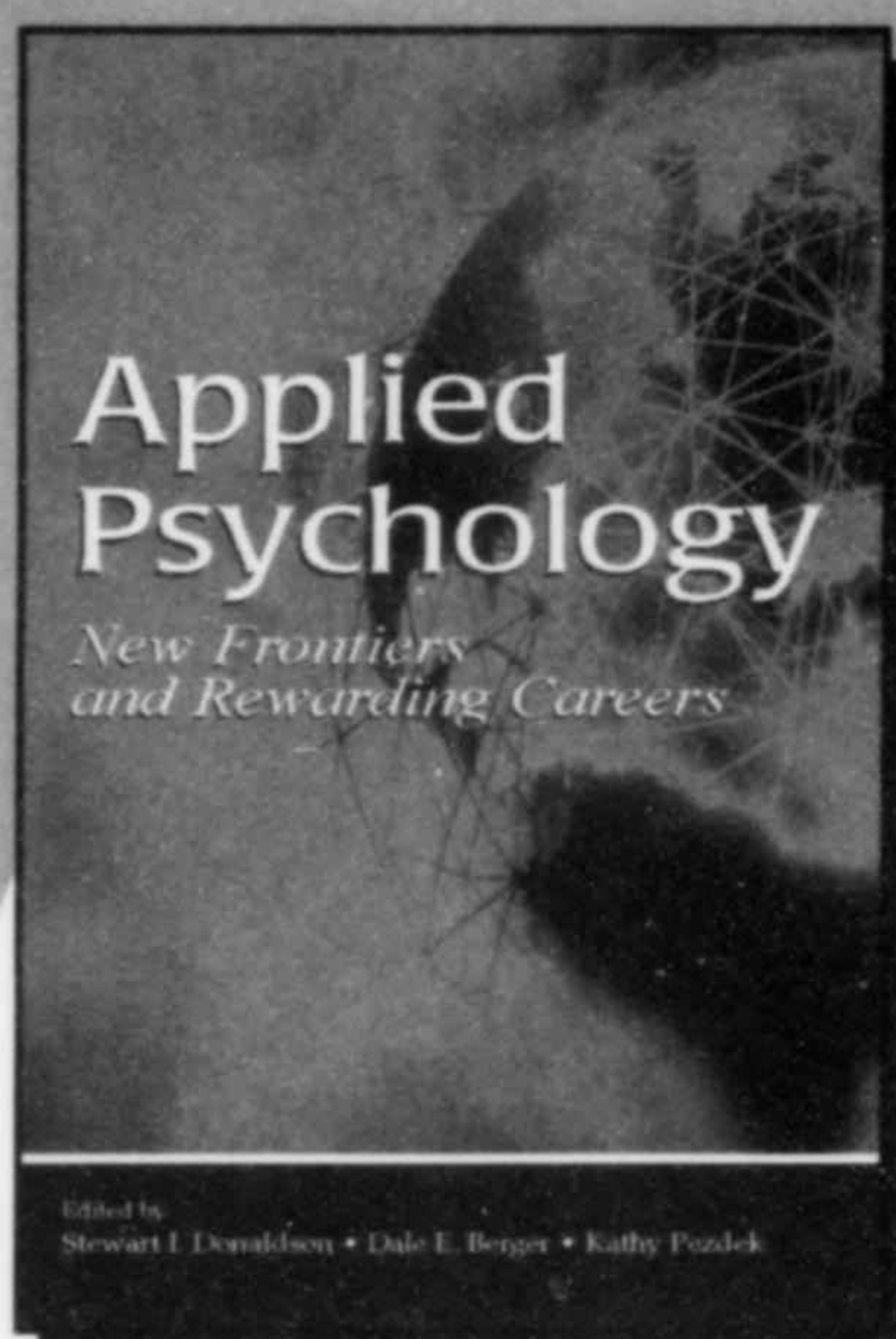
sound-producing objects under everyday circumstances than in the laboratory may require a reconsideration of the way empirical investigations are performed.

It is further argued here that requiring participants to use an abstract metric to report target location has led to the erroneous belief that observers are largely incapable of judging spatial position by sound. In a review of the literature, Middlebrooks and Green (1991) state that, "The listener's ability to localize the distance of a sound source is certainly not very good ..." (p. 148). Statements such as these appear to be correct if one limits consideration to those studies where distance was judged in feet, inches, meters, or centimeters, and where location was judged in degrees. However, when participants judge the position of sound-producing objects using an action-based metric, perceptual reports are frequently found to be highly accurate (e.g., Ashmead et al., 1995; Haber et al. 1993; Rosenblum et al., 1996). Although abstract metrics are frequently used in the investigation of auditory perception, the findings of this study, as well as other investigations, suggest that it may be prudent to reconsider that standard. The possibility exists that the use of such metrics in auditory perceptual studies may yield perceptual reports that fail to accurately represent or portray the perceptual capabilities of observers.

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APPLIED PSYCHOLOGY

New Frontiers and Rewarding Careers

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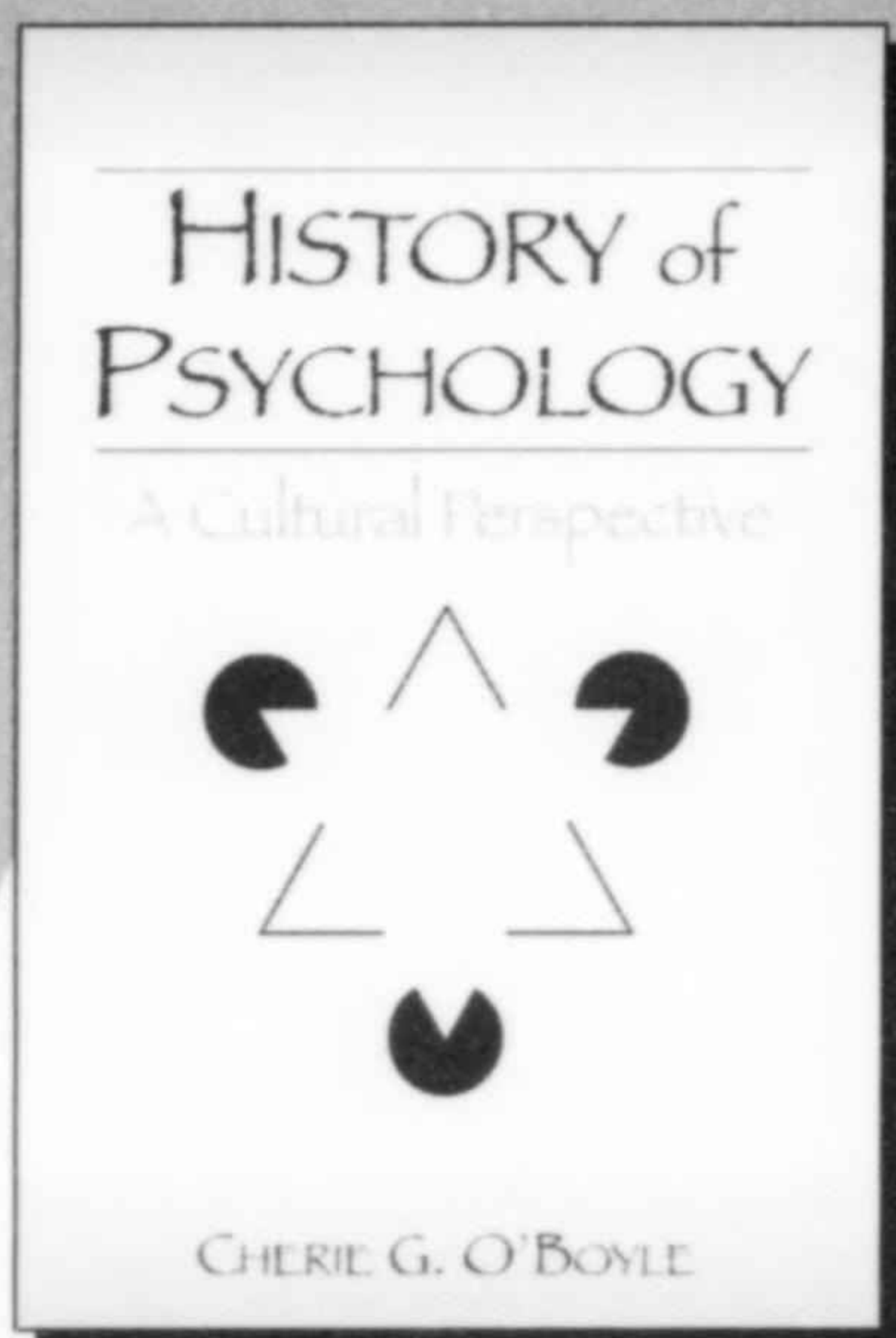
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CHERIE G. O'BOYLE

California State University, San Marcos

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