ECOLOGICAL PSYCHOLOGY, *17*(2), 75–104

Affordance Judgments and Nonlocomotor Body Movement

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In 2 experiments, participants made judgments of their own maximum sitting height. During judgments, participants stood normally or on 10 cm blocks attached to their feet. The blocks increased participants' actual maximum sitting height. For many participants, judgments changed over trials, becoming more accurate, despite the absence of practice at sitting, or feedback about judgment accuracy. Learning was observed not only when participants wore the blocks but also when they stood normally. In Experiment 2, we measured motion of the head and torso. We identified changes in body motion that corresponded to engagement in the judgment task: Across trials, sway variability was stable during judgments but increased during the intervals between judgments. Other changes in sway were limited to participants whose judgments improved over trials; that is, sway was specifically associated with learning about maximum sitting height. We discuss the results in the context of perception–action and the learning of affordances.

Affordances are opportunities for behavior that are available to a given animal (or group of animals) in a given environment (J. J. Gibson, 1979/1986; Stoffregen, 2003; cf. Turvey, 1992). One focus of the ecological approach to perception and action is the effort to understand the nature of affordances, and how animals learn about and exploit these properties of the animal–environment system. Affordances influence the outcome of our interactions with the environment, and for this reason James Gibson (1979/1986) argued that it would be adaptive for behaving or-

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ganisms to perceive affordances (rather than inferring them through cognitive processing). A growing body of research has demonstrated perceptual performance consistent with predictions made by affordance-based theories (e.g., Hirose & Nishio, 2001; Lee, Young, & McLaughlin, 1984; Stoffregen, Gorday, Sheng, & Flynn, 1999; Warren, 1984; Yonas & Hartman, 1993). The existence of affordance perception raises many questions about perception and action. In this article, we concentrate on actions that can be used to facilitate the perception of affordances.

MOVEMENT FACILITATES PERCEPTION

One of the central tenets of the ecological approach to perception and action is that perception is an act. Perception depends on movement: movement of receptors, movement of limbs, movement of the entire animal. The effects of different movements on the availability and pickup of information are not generic: Some movements create or reveal one kind of information, whereas other movements create or reveal other kinds of information. It follows that perception of particular types of information can be optimized through deployment of particular movements. This conclusion is important because perception is selective: We seek out information relevant to our goals, and ignore the rest. The selective, goal-related nature of perception provides a strong motivation to develop the skill of choosing and deploying movements that reveal information relevant to particular perceptual goals (E. J. Gibson, 2004).

A given movement can provide information about the performance of that movement. For example, taking a step can provide information about a person's walking capabilities. In addition, exploratory movement may provide information about capabilities at a more general level. This is because many affordances arise out of the same or similar relations between the animal and the environment. A surface that can be walked on by a given person may also be stood on by that person, and may be walked (and stood) on by other people. Examples from the empirical literature include taking a step to perceive catching ability (Oudejans, Michaels, Bakker, & Dolne, 1996), hefting an object to determine throwing ability (Bingham, Schmidt, & Rosenblum, 1989), movements of the head and eyes that provide information about locomotor ability (Mark, Jiang, King, & Paasche, 1999), wielding an object to learn a variety of things about it (Riley, Wagman, Santana, Carello, & Turvey, 2002), and looking at and prodding of a surface on which one might embark (Adolph, 2002; E. J. Gibson et al., 1987).

LEARNING ABOUT AFFORDANCES

Many studies of affordance learning have been conducted in a developmental context, where it has been amply demonstrated that infants spontaneously use systematic exploratory actions in learning about their action capabilities and in making decisions about actions in which to engage (for a review, see Adolph, 2002). Some studies of adults have obtained evidence that exploratory movement supports perception of relatively stable, mundane action capabilities. For example, Oudejans et al. (1996) found that when standing still, neither expert nor novice baseball players could give accurate judgments of whether they could run and catch a fly ball that would not land at their current position. Oudejans et al. also found that the accuracy of these judgments increased significantly when participants were permitted to take a single running step, while viewing the ball in flight, before making their judgments. At a more mundane level, Mark, Balliet, Craver, Douglas, and Fox (1990) found that in some cases observers' perception of their ability to sit on a chair depended on the observers' ability to move while making judgments. Findings of this kind suggest that people may not store fixed or quantitative information about their action capabilities. Rather, when estimates of action capabilities are called for, people may routinely seek out information about what they can do in the immediate situation. A person's capabilities may or may not change across situations or time scales; movement-aided perception of current capabilities may be adequate for both cases.

In the study by Oudejans et al. (1996) of fly ball catching, variations in ability across situations (trials) were implicit and were not systematically manipulated by the experimenters. Mark (1987; cf. Hirose & Nishio, 2001) systematically manipulated the maximum sitting height of his participants. Mark asked participants to make a series of judgments of their maximum sitting height under two conditions. Participants made judgments while standing normally and while wearing wooden blocks attached to their feet. Because the blocks were attached to their feet (more or less like high heels or platform shoes), they increased participants' maximum sitting height by an amount equal to block height (10 cm). In the normal stance condition, judgments were stable across trials, and were accurate. When wearing blocks, initial judgments were inaccurate, but over the series of 12 trials judgments gradually shifted until, near the end of the series, judgments accurately reflected maximum sitting height as altered by the blocks. The data seem to clearly indicate that participants learned about their changed action capabilities, and did so over a brief series of judgments. Perhaps the most remarkable feature of the outcome was that participants received no feedback about judgment accuracy and were not permitted to sit while wearing the blocks (that is, they had no practice at performing the act that they were being asked to judge). With no practice and no feedback, how did participants learn about the block-induced increase in sitting height? Mark suggested learning might have been facilitated by movements in which participants engaged while wearing the blocks. In the study of Oudejans et al. (1996), the movement that facilitated perception was a part of the act that participants were asked to judge. They were asked to judge whether they could catch a ball by running, and judgment accuracy increased when they were permitted to take one running step before making their judgments. Unlike Oudejans's studies, Mark's participants did not begin the act that they were being asked to judge. This suggests that informative movement used by Mark's participants may not have been directly related to the act of sitting.

BODY MOVEMENT FACILITATES AFFORDANCE PERCEPTION

Mark et al. (1990) addressed the possibility that movement can support affordance learning. In their Experiment 2, participants stood still while wearing the blocks (i.e., they did not walk or move their feet). Judgments were more variable than in Mark (1987), in which participants walked while wearing the blocks, but the overall pattern was the same. This experiment (Mark et al., 1990) appeared to indicate that body sway was sufficient for learning about changes in maximum sitting height. In Experiment 3, participants viewed the experimental chair apparatus through a monocular peephole. The peephole limited the field of view but also placed unusual restrictions on postural control (participants had to stand very still so as to maintain the correct eye position). The peephole nullified learning; in the block condition judgments were inaccurate and did not change across trials (judgment variability across participants was also significantly increased). However, judgments without blocks were also affected. In fact, judgments with and without blocks were essentially identical. In Experiment 4, participants adopted an awkward stance (heels together, toes apart), which tended to increase body sway (so much so that it was visible to the experimenters). The judgment data were essentially identical to those obtained using the peephole. This result indicates that in Experiment 3 the restricted field of view caused by the peephole did not explain the loss of learning. In Experiment 5, Mark et al. eliminated body sway by asking participants to stand with their backs and back of their head pressed against a wall. Here, again, in both the block and no block conditions participants gave inaccurate judgments that did not improve over trials. Mark et al. (1990) interpreted their results as indicating "the importance of information-gathering activities, including exploration, for the perception of body-scaled information about affordances" (p. 353). They went on to note that although these activities are important when the observer's capabilities have been altered (i.e., while wearing the blocks) "our results underscore the importance of information gathering activities even under previously encountered conditions where the observer supposedly is familiar with his or her action capabilities" (p. 353); that is, when not wearing the blocks.

THE USES OF BODY SWAY

One way to describe the findings of Mark et al. (1990) is that body sway can be sufficient for learning about suprapostural capabilities. Such a description suggests that body sway may have uses that differ substantially from what has been imagined under classical views of postural control. Classically, scientists have tended to assume that body sway is "noise," and that the main (or sole) purpose of postural control actions is to maintain the body's center of mass above the feet; that is, to avoid falling (e.g., Horak & MacPherson, 1996; Woollacott & Shumway-Cook, 2002). Recently, this classical view has been challenged by a variety of studies showing that variations in postural sway (head and torso) often have functional relations to suprapostural activity, that is, to activity that is not defined or evaluated in terms of sway (e.g., Bardy, Marin, Stoffregen, & Bootsma, 1999; Oullier, Bardy, Stoffregen, & Bootsma, 2002; Riccio, 1993; Riccio & Stoffregen, 1991; Riley, Mitra, Stoffregen, & Turvey, 1997; Riley, Stoffregen, Grocki, & Turvey, 1999; Stoffregen, Bardy, Bonnet, Pagulayan, & Hove, 2005; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Stoffregen, Smart, Bardy, & Pagulayan,1999; Wulf, Weigelt, Poulter, & McNevin, 2003).[1]

One possibility is that body sway can provide information about postural dynamics (Riccio, 1993; Riley et al., 1997) or, more generally, about some of the dynamics of the animal–environment system. Riley et al. showed this in the context of leaning. Leaning introduces an asymmetry into postural dynamics. Blocks worn on the feet also change postural dynamics, in terms of relations between body sway and perceptual information. For example, blocks increase the height of the head and eyes above the ground. This means that the optic flow created by a given amount of body sway will differ; the axis of rotation (assuming primarily ankle sway) will be higher, the overall velocity of flow will be reduced (i.e., the gain between sway velocity and optic flow velocity will be different), and so on. In addition, there will be changes in relations between the optical and gravitoinertial stimulation created by sway; here, too, the constant of proportionality will differ. Body sway generates global array patterns (Stoffregen & Bardy, 2001) that provide information about physical distance (Bingham & Stassen, 1994), and these global array patterns are picked up and used (Bingham & Pagano, 1998).

INFORMATION ABOUT AFFORDANCES

Ideally, the role of movement in affordance perception should begin with formal models of the information that specifies affordances. Presumably, such models would provide guidance about the types of movements that would generate or optimize the relevant information that would, in turn, lead to testable hypotheses about the relation of specific types of movements to affordance learning and perception. Despite their obvious value, we know of no formal models of the information that specifies

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[1] Among other things, this new view raises questions about the definition of body sway: If postural motion has utility above and beyond postural stabilization, then is there a clear boundary between postural control and any other type of body movement? In this study, we did not attempt to distinguish postural control from any other type of body movement (see Experiment 2).

any affordance (Stoffregen, 2000, 2003; Stoffregen, Gorday, et al., 1999). There are many formal models of information, such as τ (e.g., Lee, 1976) and optic flow (e.g., Lee, 1980). There are also formal models of how particular movements can generate particular types of information (e.g., Bingham & Stassen, 1994). None of these models has been claimed to formalize information about a specific affordance, including maximum sitting height. Empirical data can help in the process of model building, for example, by providing guidance about the parameters that should be included in models. In conducting this study, this was one of our goals.

THIS STUDY

We sought to obtain quantitative evidence about how body sway can facilitate perceptual–motor learning about maximum sitting height. To our knowledge, ours is the first study to attempt quantification of movement patterns used in the perception of affordances. In the absence of formal models of information specifying maximum sitting height, we took an exploratory approach based on the empirical facts at hand. Mark et al. (1990) found that ordinary body sway was sufficient for learning about maximum sitting height, and on this basis we predicted that the accuracy of judgments of maximum sitting height would be associated with parameters of body movement. We elected to quantify body motion using dependent variables commonly used in research on the perception and control of stance, specifically, the positional variability of the head and torso. Previous studies demonstrated a functional link between these variables and simultaneous suprapostural activity, such as looking (e.g., Stoffregen et al., 2005; Stoffregen et al., 2000; Stoffregen, Smart, et al., 1999) and touching (Riley, Stoffregen, et al., 1999). In these studies, the magnitude of body sway (as operationalized by the standard deviation of head or torso position) was related to participants' suprapostural task. These studies suggest that the magnitude of sway might influence a person's ability to look at a chair and make a judgment about whether it is low enough to sit on.

We repeated the general experimental protocol used by Mark et al. (1990). The primary difference in our study was that we collected quantitative data about motion of the head and torso during the making of perceptual judgments about maximum sitting height. Participants were treated in accordance with the ethical principles of psychologists and code of conduct (American Psychological Association, 1992), and the experimental protocol was approved by the University of Minnesota Institutional Review Board.

EXPERIMENT 1

We elected to focus on Experiment 2 from the study by Mark et al. (1990). In this experiment, participants made a series of judgments of maximum sitting height while standing normally or while wearing blocks that increased their maximum sitting height by 10 cm. Participants were not permitted to walk during the judgment phase of the experiment (while wearing blocks or without blocks).

Pilot studies suggested that it would be difficult to produce an exact replication of the results of this experiment. In particular, we found that subtle variations in experimental method influenced judgments of maximum sitting height. For example, in one pilot study the blocks were attached while participants sat in a chair with their feet on the floor, lifting each foot so that the block could be attached. In this pilot study, no learning was observed in the block condition (across trials). No learning was needed: Judgments of maximum sitting height while wearing the blocks were accurate on the first or second trial. Evidently, the joint angles associated with donning the blocks with feet on floor, or the changes involved in rising from the chair while wearing blocks, or both, provided enough information for recalibration (similar to the effect of practicing sitting only two or three times, as in Experiment 6 of Mark et al., 1990). Mark (personal communication, 2002) revealed that when the blocks were attached in the Mark et al. study, participants sat on a table such that their feet dangled above the floor. These subtle effects emphasize the fact that although body sway may be sufficient for affordance learning, it is not necessary. Given these effects, we decided to begin by attempting an exact replication of the effect of blocks on affordance judgments.

Method

Participants. Twelve University of Minnesota undergraduate students, 5 men and 7 women, participated on a volunteer basis. They ranged in age from 18 to 38 years, and in height from 1.47 to 1.94 m. All participants were naïve to the hypotheses of the experiment.

Apparatus. The experimental chair was the same one used by Stoffregen, Gorday, et al. (1999), which was a copy of the one used by Mark (1987). It consisted of a vertical plywood backboard (92 cm wide by 152 cm high) to which was attached a horizontal seat pan. The height of the seat pan could be adjusted between 43 cm and 126 cm, moving along a track attached to the backboard. The seat pan and backboard were painted a light shade. The experimental chair was modified so that the seat pan was raised and lowered by an electric motor under control of the experimenter (in Stoffregen, Smart, et al., 1999, the seat pan was moved by hand). Velocity of up and down movement was 2 cm per sec. The motor was connected to the controller by a long cable that permitted the experimenter to be seated behind the participant (and out of his or her view). A rope attached to the seat pan ran over the top of the apparatus and down the back to the motor, which was attached to the bottom of the backboard. A tape measure attached to the back of the apparatus was used to measure seat-pan adjustments. A needle inserted horizontally through the rope was calibrated to the tape measure. A digital video camera recorded the needle and tape measure;

metric data on seat-pan height were taken from the video record. The experimenter controlled the seat-pan height visually, from his perspective behind the experimental participant.

The blocks were solid wood 22 cm long, 8 cm wide, and 10 cm high. Each block was fitted with Velcro straps that could be adjusted to fit snugly over the ball and arch of the foot.

Procedure. We copied the procedure of Experiment 2 from Mark et al. (1990). Half of the participants began with the block condition, and half with the no block condition.

Participants were run individually. They were first asked to remove their shoes. Observers stood approximately 3.3 m from the experimental chair. Following a demonstration of the mobility of the seat pan on the experimental chair, instructions were read. Each observer completed 12 trials in the block condition, and 12 in the no block condition. Each trial consisted of a pair of judgments, one with the seat pan moving up from the bottom, and one with the seat pan moving down from the top. There were no practice trials, and observers received no feedback on their performance. Following Mark et al. (1990), observers stood upright in one location for the duration of each condition but were able to move their head and eyes, to lean forward or back, and to make adjustments to maintain stance. Also following Mark et al., we did not tell participants not to move their feet. Prior to the block condition, the participant was asked to sit on a table whose surface was sufficiently high that the participant's feet dangled at least 20 cm above the floor. Participants were instructed to avert their gaze while the experimenter unpacked the blocks and affixed them to their feet. Participants were not permitted to see the blocks at any time prior to or during the experiment. Participants were not permitted to walk while wearing the blocks.

Following Mark et al. (1990), we defined sitting as an act in which (a) in moving from a standing to a sitting posture, both feet must remain flat on the ground; (b) when seated, the actor must be able to lift both feet straight off the floor without placing his or her hands on the seat pan to stabilize the body, and without losing balance or leaning backward; and (c) the pelvis, but not the thighs can rest on the seat pan. The experimenter demonstrated acts of sitting that met this definition, and some that did not. Maximum sitting height was defined as the highest seat-pan height at which a given actor would be able to sit without violating the definition.

We used a version of the method of limits (Gescheider, 1985; Stoffregen, Gorday, et al., 1999). After a ready signal the experimenter began to move the seat pan. Motion continued smoothly until the participant said "stop." At this point the participant was allowed to give instructions to the experimenter to make small adjustments in seat-pan height. When the participant gave his or her approval of the seat-pan setting, the seat pan was then moved to the starting position for the next judgment, and the process repeated.

Following experimental trials we collected data from the observers on their sitting capabilities and anthropometrics, using the method of Mark (1987; Mark et al., 1990; Stoffregen, Gorday, et al., 1999). Sitting capabilities were measured using a height-adjustable office chair. Each person's maximum sitting height was measured by having him or her sit on the chair in the manner prescribed by the definition of maximum sitting height. The chair was raised or lowered to find the maximum height.

Results

The judgment data are summarized in Figure 1. The main effect of viewing condition (block vs. no block) was not significant, $F(1, 22) < 1$, *ns*. The overall main effect of trials was significant, $F(11, 242) = 2.928$, $p < .05$, accounting for 11.7% of the variance. The interaction between block and trials was not significant, $F(11,242) = 1.204$, *ns*. The slope of the regression for the no block condition was –0.07, which did not differ from 0, $t(142) = –0.35$, *ns*. The slope of the regression for the block condition was –0.30, which was significantly different from 0, $t(142) = –1.99$, $p < .05$. For each condition, our criterion for learning was that the slope of the regression function for the group data differed significantly from 0, and that the slope was in the direction of increasing accuracy. By this criterion, we concluded that learning occurred in the block condition but not in the no block condition.

We evaluated the possibility that learning was affected by the order in which no block and block conditions were presented. Table 1 presents the slope of the regressions of judgments across trails as a function of condition and the order of conditions. Slope was not influenced by condition order in the no block condition, $t(140) = –0.30$, *ns*, or in the block condition, $t(140) = –0.178$, *ns*. In the block condition, the mean (across participants) absolute difference was 5.40 cm (*SD* = 6.38), whereas it was 6.45 cm (*SD* = 8.50) in the no block condition.

We examined the possibility that learning occurred differentially across participants. Post hoc identification of different groups is common in learning research (e.g., Bardy, Faugloire, & Stoffregen, 2005), and in research on perception–action (e.g., Warren, Kay, & Yilmaz, 1996). Like Warren et al., we were interested mainly in those who exhibited postural learning; we wanted to find out how they did it. Participants were placed in learning and nonlearning groups based on the slope of the regression for their judgments over trials. The regression was computed for each individual. Individuals with slopes that differed significantly from 0 (by *t* test) and whose judgments trended toward increasing accuracy across trials were included in the learning group; all other participants were included in the nonlearning group. Learning and nonlearning groups were defined independently for the no block and block conditions; this reflects the fact that some individuals exhibited learning on one condition, but not in the other.

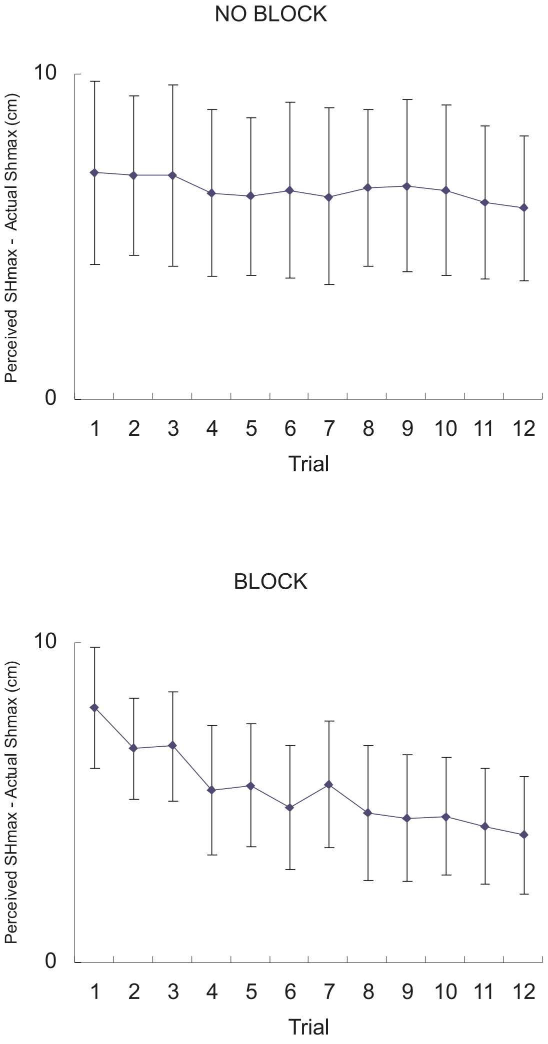


FIGURE 1 Judgment data as a function of condition, Experiment 1. Mean difference in centimeters between perceived and actual maximum seat height across trials in the No Block (top) and Block (bottom) conditions. Error bars represent standard error.

For the no block condition, 5 people were in the learning group (1 man and 4 women), and 7 were in the nonlearning group. The slope (–0.282) of the regression of the learning group was significantly greater than 0, $t(58) = -2.148$, $p < 0.05$. The slope (–0.013) of the regression of the nonlearning group did not differ from 0, $t(82) = -0.241$, *ns*. On Trial 12, the judgments of the learning group were accurate;

TABLE 1
Slope of the Regression of Judgments Across Trials as a Function of Condition and Condition Order, Experiment 1

	Condition	
Condition Order	*No Block*	*Block*
No Block first, Block second	–0.017	–0.258
Block first, No Block second	–0.130	–0.352

that is, the judgments did not differ from actual maximum sitting height for the no block condition, $t(4) = 0.825, p > .05$). As might be expected, for the nonlearning group, judgments were inaccurate throughout. In the no block condition, judgments on Trial 1 differed from zero error, $t(6) = 4.457, p < .05$; judgments on Trial 12 also differed from zero error, $t(6) = 3.164, p < .05$.

For the block condition, 6 participants (3 men and 3 women) were placed in the learning group, leaving six in the nonlearning group. The slope (–0.304) of the regression for the learning group was significantly different from 0, $t(70) = –2.893$, $p < .05$, while the slope (–0.02) of the regression for the nonlearning group did not differ from 0, $t(70) = –0.421$, *ns*. For the learning group, judgments on Trial 12 did not differ from zero error, $t(5) = 0.739, p > .05$. For the nonlearning group, judgments on Trial 1 differed from zero error, $t(5) = 3.382, p < .05$; judgments on Trial 12 also differed from zero error, $t(5) = 2.928, p < .05$).

Discussion

We found an overall learning effect in the block condition, replicating the group effect reported by Mark et al. (1990). But we found some participants learned, whereas others did not. This may have been true in Mark's studies, as well. Mark's inferential testing was confined to group data. For our group data, learning was limited to the block condition. Our participants began with overestimates; in most of the experiments reported by Mark et al., participants began with underestimates (cf. Hirose & Nishio, 2001).

After 12 judgments in the block condition, participants were accurate in judging maximum sitting height. As in previous studies (Mark, 1987; Mark et al., 1990), this was true despite the absence of practice (sitting) or feedback about judgment accuracy. The increase in accuracy across judgments is consistent with Mark et al.'s conclusions that body sway is sufficient for participants to learn how the blocks had influenced their maximum sitting height.

Our analysis of data from individual participants revealed that some individuals learned whereas others did not. In the block condition some participants did not learn despite the overall learning observed in the group data. Interestingly, in the no block condition some participants learned, despite the overall absence of learning in the group data. The occurrence of these individual differences in both conditions had implications for our analysis of movement data in Experiment 2.

EXPERIMENT 2

Experiment 2 was the same as Experiment 1, with a larger *n*, and with the addition of measurement of head and torso motion. The larger number of participants increased our ability to do post hoc identification and analysis of learning and nonlearning groups. As in Experiment 1, we did not impose strict constraints on stance during the experimental session, beyond the requirement to stand in one location. Our intention was to match as closely as possible the method used by Mark et al. (1990). So long as participants followed our instructions, we accepted any activity during our measurement of head and torso movement. Our instructions contrast with the common practice in research on postural control, in which participants are asked to stand as still as possible, not to move their feet, and so on (e.g., Hunter & Hoffman, 2001; Lee & Lishman, 1975). As noted in the introduction, recent research suggests that there may be no clear boundary between postural and suprapostural movement (e.g., Bardy et al., 1999; Riccio & Stoffregen, 1988; Stoffregen et al., 2000; Stoffregen, Smart, et al., 1999). For these reasons we chose to accept all movements that were in compliance with our instructions.

Method

Participants

Twenty-four University of Minnesota undergraduate students, 4 men and 20 women, participated on a volunteer basis. They ranged in age from 18 to 36 years, and ranged in height from 1.52 to 1.95 m. All were naïve to the hypotheses of the experiment.

Apparatus and Procedure

The apparatus and procedure were the same as Experiment 1, with the following changes. Kinematic data were recorded using a magnetic tracking system (Flock of Birds, Ascension Technologies, Burlington, Vermont). Participants wore a bicycle helmet to which was attached a receiver. A second receiver was attached to the skin between the shoulders, using cloth medical tape. A third receiver was attached to a metal protractor so that it could be moved back and forth in a semicircle by the experimenter. This receiver was moved at the beginning of each judgment, when the seat pan began to move, and again at the end of each judgment, when the participant indicated he or she was satisfied with the position of the seat pan. In each condition, sway was recorded continuously across the duration of the

12 judgment trials, at a sampling frequency of 40 Hz. Before experimental trials, quiet stance was recorded for 60 sec, without blocks.

Results

Judgments

Mean judgment data for no block and block conditions are shown in Figure 2. The main effect of conditions (block vs. no block) was not significant, $F(1,46) = 3.624$, $p > .05$. The main effect of trials was significant, $F(11,506) = 10.046$, $p < .05$, accounting for 17.9% of the variance. The interaction between condition and trials was not significant, $F(11,506) < 1$, *ns*.

Table 2 presents the slope of the regression of judgments across trials as a function of condition and condition order. Slope was not influenced by condition order in the no block condition, $t(284) = 1.1$, $p > .05$, or in the block condition, $t(284) = 0.396$, $p > .05$. In the block condition, the mean (across participants) absolute difference was 3.23 cm (*SD* = 7.43), whereas it was 6.83 cm (*SD* = 6.28) in the no block condition.

As in Experiment 1, we placed individual participants into learning and nonlearning groups. Data from the no block and block conditions were considered separately. This made it possible for individual participants to be in the learning group for both the no block and block conditions, for only one condition, or for neither condition.

In the no block condition, the learning group was composed of 11 women, who had a group slope of –0.599, which differed from 0, $t(130) = -4.48$, $p < .05$. The nonlearning group was composed of 13 participants, and had a group slope of –0.049, which did not differ from 0, $t(154) = 0.842$, $p > .05$. On Trial 12, the judgments of the learning group were not accurate (they differed from actual maximum sitting height, $t(10) = 4.592$, $p < 0.05$, indicating that learning was incomplete. As might be expected, for the nonlearning group, judgments were inaccurate throughout, with judgments differing from zero error at the beginning, Trial 1, $t(12) = 2.645$, $p < .05$ and end of testing, Trial 12, $t(12) = 2.316$, $p < .05$. The learning group in the no block condition needed to learn (initial judgments were inaccurate), but their learning was incomplete. The nonlearning group in the no block condition needed to learn, but failed to do so.

For the block condition, a learning group composed of 9 women had a group regression slope for judgments of –0.358, which differed significantly from zero, $t(106) = -2.66$, $p < .05$. The nonlearning group (block condition), composed of 15 participants, had a group slope of –0.03, which did not differ from 0, $t(178) = -1.003$, $p > .05$. On Trial 12, the judgments of the learning group differed from actual maximum sitting height, $t(8) = 2.703$, $p < 0.05$. For the nonlearning group in the block condition, the group mean did not differ from actual maximum sitting height at the first trial, Trial 1, $t(14) = 1.969$, $p > .05$, or at the last trial, Trial 12,

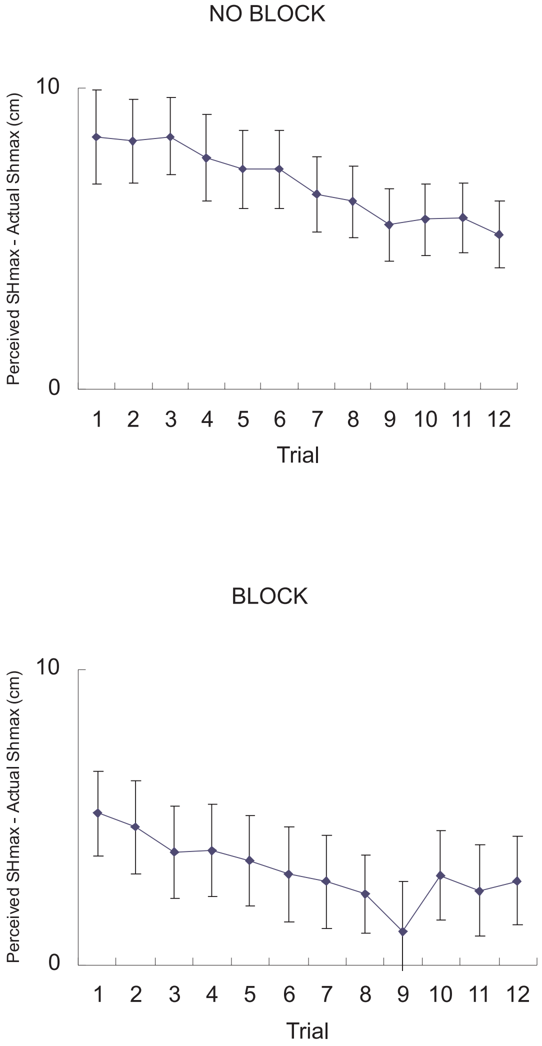


FIGURE 2 Judgment data as a function of condition, Experiment 2. Mean difference in centimeters between perceived and actual maximum seat height across trials in the no block (top) and block (bottom) conditions. Error bars represent standard error.

$t(14) = 1.008$, $p > .05$. However, for most participants, judgments were not accurate. This is revealed by considering data from individual participants (Figure 3). Thus, the learning group needed to learn (initial judgments were inaccurate), and they did learn (although their learning was incomplete). By contrast, the nonlearning group also needed to learn, but failed to do so. The inaccurate judg-

TABLE 2
Slope of the Regression of Judgments Across Trials as a Function of Condition and Condition Order, Experiment 2

	Condition	
Condition Order	*No Block*	*Block*
No Block first, Block second	–0.341	–0.284
Block first, No Block second	–0.110	–0.185

ments and extreme intraparticipant variability in the nonlearning group closely resembles a result of Mark et al. (1990, Experiment 3). The between-participants variability of judgments did not differ between the nonlearning group in the no block condition and the nonlearning group in the block condition, $t(26) = 0.42$, $p > .05$, indicating that the wide individual differences observed in the block condition for this group (Figure 3C, D, E) also obtained in the no block condition.

Head and Torso Motion

As noted in the introduction, we focused on the magnitude of motion, which we defined operationally as the standard deviation of position. Data on head and torso motion were analyzed separately in the anterior–posterior (AP) and mediolateral (ML) axes. When including all 24 participants and all data from the continuous recordings, there were no differences between the no block and block conditions, each $t < 2.069$, $p > .05$.

We reasoned that effects on body sway might be limited to the time during which participants were engaged in making judgments. To evaluate this possibility, data from experimental conditions were parsed into judgment intervals and interjudgment intervals. Judgment intervals began when the seat pan began to move and ended when the participant indicated that his or her judgment was final. Sample data from judgment and interjudgment intervals are shown in Figure 4. In the no block condition, the mean duration of judgment intervals was 19.61 sec, whereas in the block condition the mean was 19.66 sec. For judgment intervals, there were no differences in sway between no block and block conditions in the AP or ML axis for head or torso, each $t < 2.069$, $p > .05$. However, collapsed across participants and conditions (no block and block), sway during judgment intervals was significantly reduced relative to sway in the interjudgment intervals (i.e., between judgments), for AP motion of the head, $t(94) = 2.481$, $p < .05$ (Figure 5), and for AP motion of the torso, $t(94) = 3.183$, $p < .05$ (Figure 6). For head motion in the AP axis, the interaction between trials and intervals (judgment interval vs. interjudgment interval) was significant, $F(22,484) = 1.579$, $p < .05$. This interaction is illustrated in Figure 7. It reveals that postural control was influenced by the variation in suprapostural task (making judgments vs. not making judgments). Differences in the ML axis were not significant for head or torso.

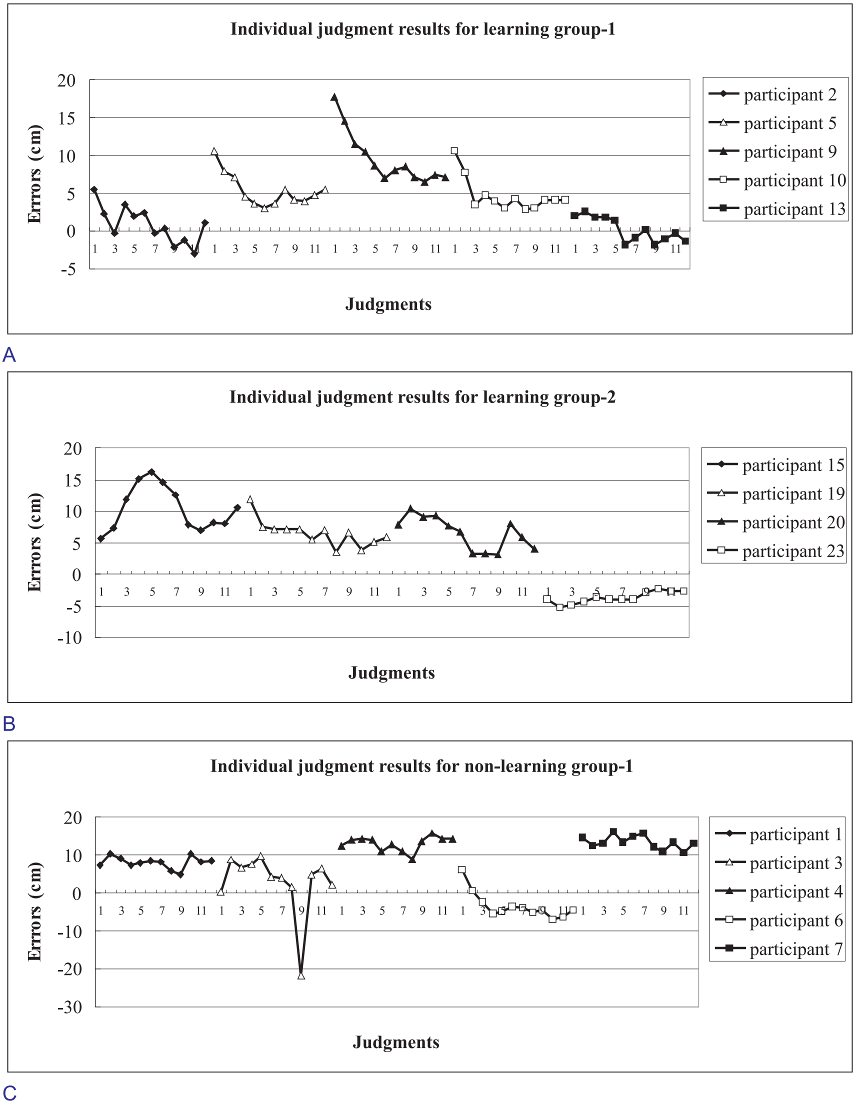
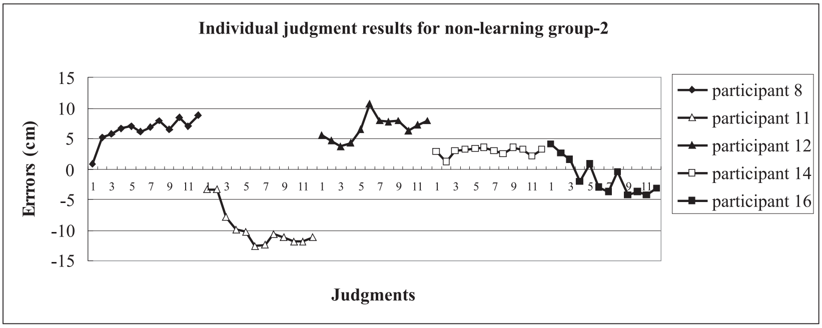


FIGURE 3 Judgment data (block condition) for individual participants as a function of trial, Experiment 2. A and B: Participants in the learning group. C, D, and E: Participants in the nonlearning group.



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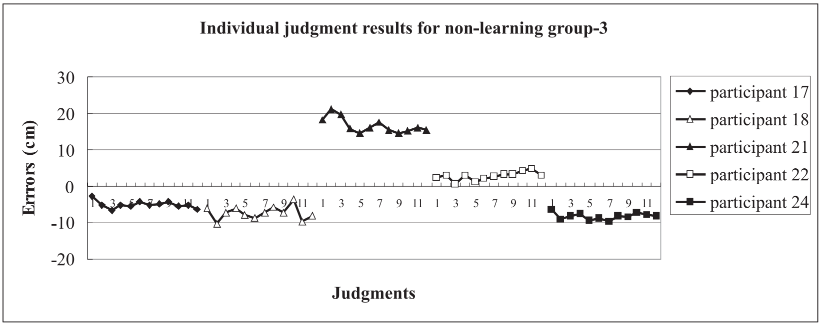


E

FIGURE 3 *(Continued)*

Learning and Nonlearning Groups

We compared motion data for the learning and nonlearning groups in the no block and block conditions. The mean duration of judgment intervals for the learning group in the no block condition was 19.99 sec, and 19.37 sec for the learning group in the block condition. The mean duration of interjudgment intervals for the nonlearning group in the no block condition, was 19.28 sec, and 19.83 sec for the nonlearning group in the block condition.

The learning and nonlearning groups did not differ in motion of the head or torso, in the AP or ML axis, as a function of condition (no block vs. block), as a function of trials, or as a function of interval (judgment vs. interjudgment), each $t < 2.064$, $p > 0.05$).

We next compared sway during the first judgment interval with sway in the control trial (i.e., sway during quiet stance before any judgments). These tests permitted us to determine whether sway changed between the control trial and the beginning of the judgment task (which followed immediately after the control trial). We chose the first 20 sec of the control trial to match the mean duration of the judgment and interjudgment intervals (both were about 20 sec, as noted previously).

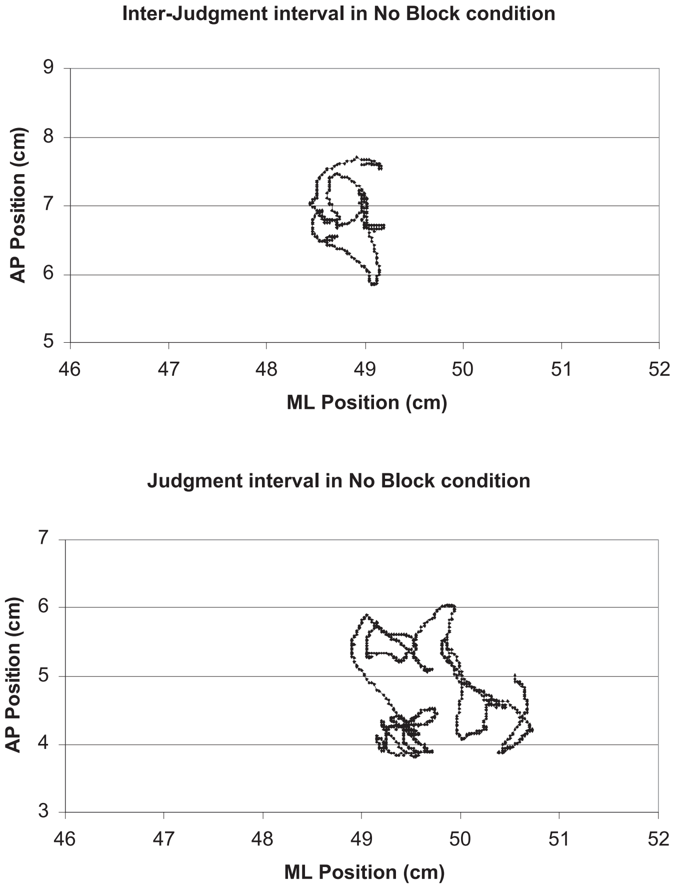
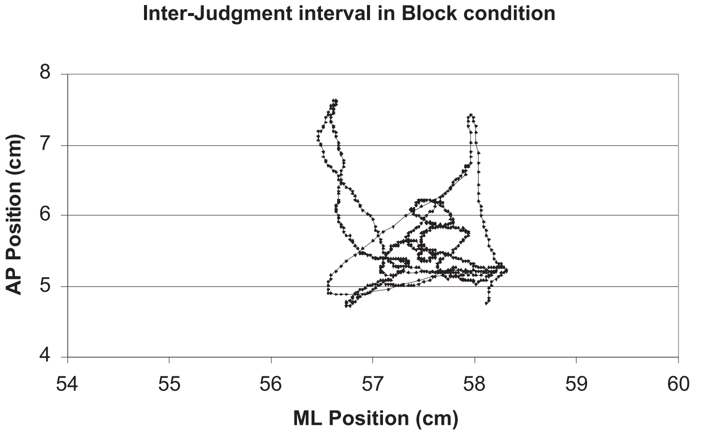


FIGURE 4 Sample data showing motion of the head for a representative participant in Experiment 2. Each graph shows data from one interval, lasting approximately 15 sec.

In the no block condition, there were significant increases in the learning group for motion of the head in both the AP and ML axes during the first judgment, as compared to the first 20 sec of the control trial, $t(10) = 2.618, p < .05$; $t(10) = 3.289, p < .05$, respectively, as illustrated in Figure 8. The were also significant increases in AP and ML motion of the torso, $t(10) = 2.307, p < .05$; and $t(10) = 2.233, p < .05$, respectively; Figure 9. Differences in the nonlearning group were not significant. In the block condition, there was a significant difference in the learning group for motion of the head in the ML axis, $t(8) = 2.425, p < .05$; Figure 10. In the nonlearning group there were no significant differences. In these comparisons, all significant differences involved the learning group. The finding of significant differences in both the no block and block conditions indicates that the changes in sway during judgments were not an effect of wearing of the blocks per se, but rather of the activity involved in learning about maximum sitting height either with or without the blocks.


Inter-Judgment interval in Block condition

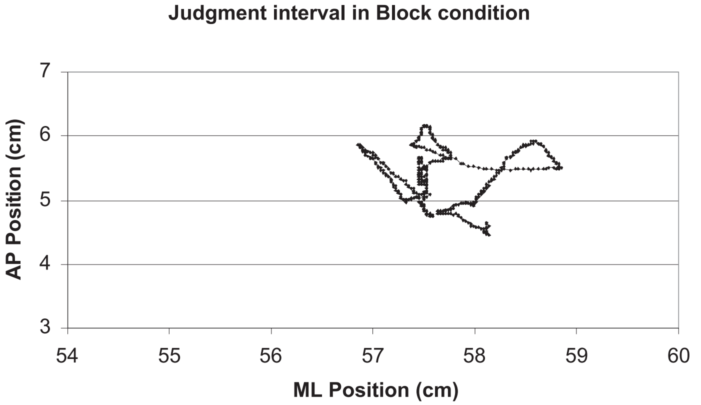

Judgment interval in Block condition

FIGURE 4 *(Continued)*

Control condition. Mean values of sway during the 60 sec control trial are presented in Figure 11. To determine whether there was any difference in baseline postural motion between participants who learned and those who did not, we compared sway for the 15 participants who learned in either or both experimental conditions with sway for the 9 participants who did not learn in either experimental condition. Learning and nonlearning groups did not differ in sway during the 60 sec control trial, each $t < 1.3$, $p > .05$.

Discussion

Judgments. As in Experiment 1, participants in Experiment 2 tended to overestimate their maximum sitting height. This was true when participants were wearing the blocks, but also when they were not (Figure 2). It was also true for those participants who learned about their maximum sitting height, and for those

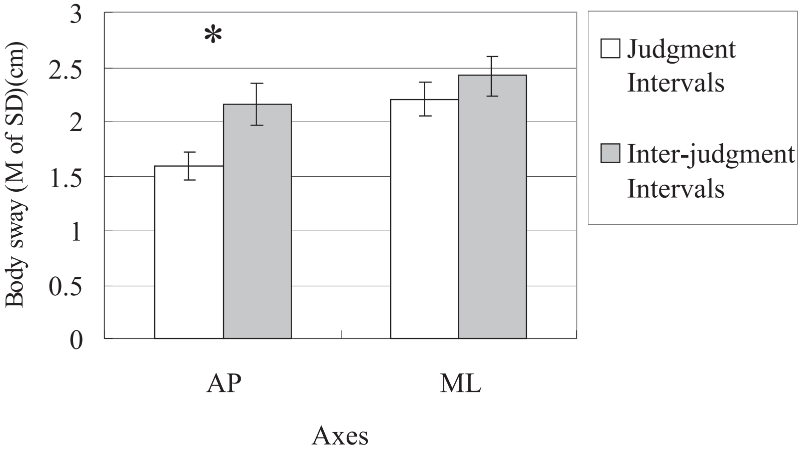


FIGURE 5 Experiment 2. Mean head motion during judgment and interjudgment intervals for head motion, collapsed across conditions (no block and block) and groups (learning and nonlearning). *$p < .05$.

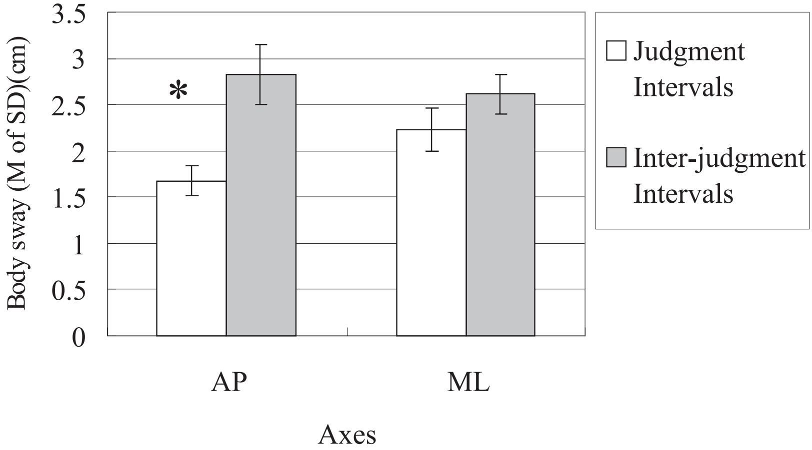


FIGURE 6 Experiment 2. Mean torso motion during judgment and interjudgment intervals, collapsed across conditions (no block and block) and groups (learning and nonlearning). Error bars are standard error. *$p < .05$.

who did not (Figure 3). The overestimates exhibited by our participants contrast with Mark et al. (1990), who found underestimates in most viewing conditions. However, in some conditions Mark et al. found overestimates (e.g., Experiment 6), as did Hirose and Nishio (2001).

Several of our participants exhibited accurate judgments on the first trial while wearing the blocks, despite the absence of practice; several participants also exhib-

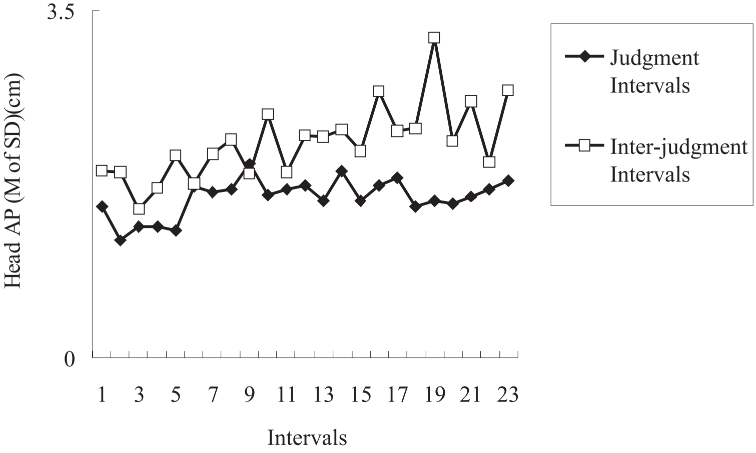


FIGURE 7 The significant interaction between intervals and trials for head motion in the AP axis, Experiment 2, collapsed across conditions (no block and block) and groups (learning and nonlearning).

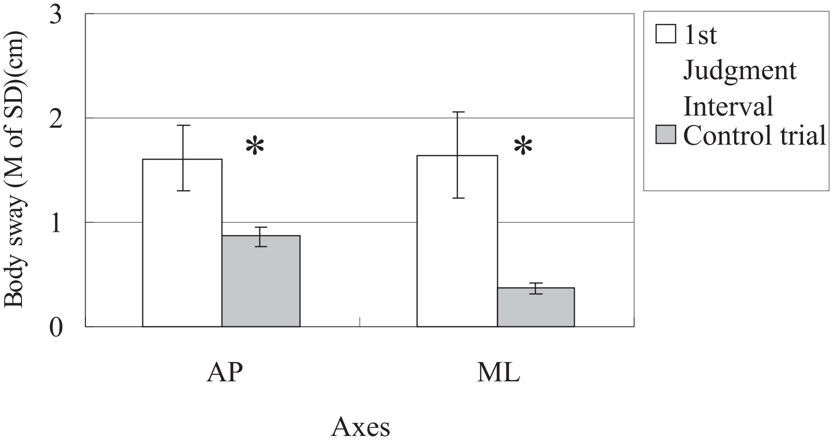


FIGURE 8 Mean head motion in the learning group, no block condition, Experiment 2. White bars: Sway during the first judgment interval. Gray bars: Sway during the first 20 sec of the control trial. $*p < .05$. The error bars are standard error.

ited first trial accuracy in the no block condition. First trial accuracy while wearing the blocks is not readily attributable to stored information about maximum sitting height (i.e., memory). First trial accuracy may be an effect of movements prior to the onset of data collection.

Role of sway in perception. Mark et al. (1990) found that the elimination of body sway was associated with the elimination of affordance learning in a novel

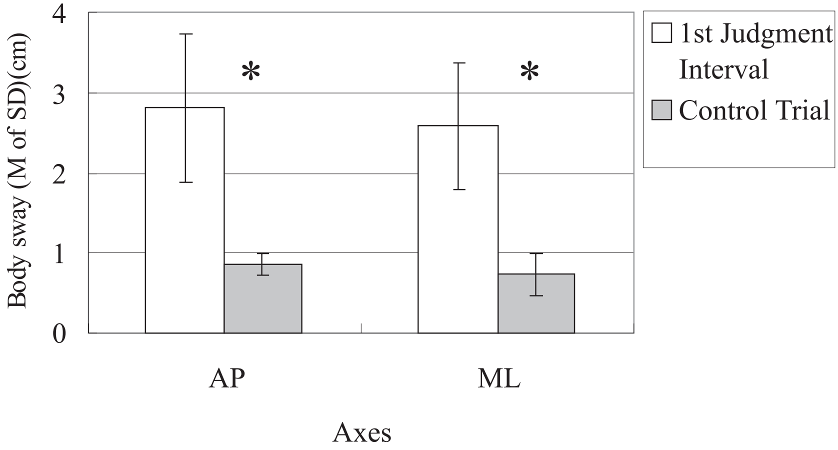


FIGURE 9 Mean torso motion in the learning group, no block condition, Experiment 2. White bars: Sway during the first judgment interval. Gray bars: Sway during the first 20 sec of the control trial. *$p < .05$. The error bars are standard error.

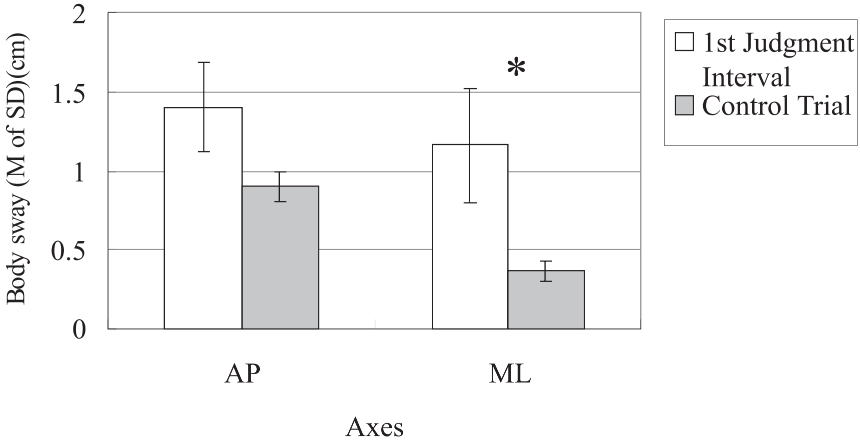


FIGURE 10 Mean head motion in the learning group, block condition, Experiment 2. White bars: Sway during the first judgment interval. Gray bars: Sway during the first 20 sec of the control trial. *$p < .05$. The error bars are standard error.

condition (block). However, they found the absence of sway also prevented accurate perception maximum sitting height in a familiar condition (no block). Our data illuminate these effects in the context of measured sway: In both the no block and block conditions, sway during judgments differed from sway between judgments, and differed from sway in the control trial. These results suggest that sway

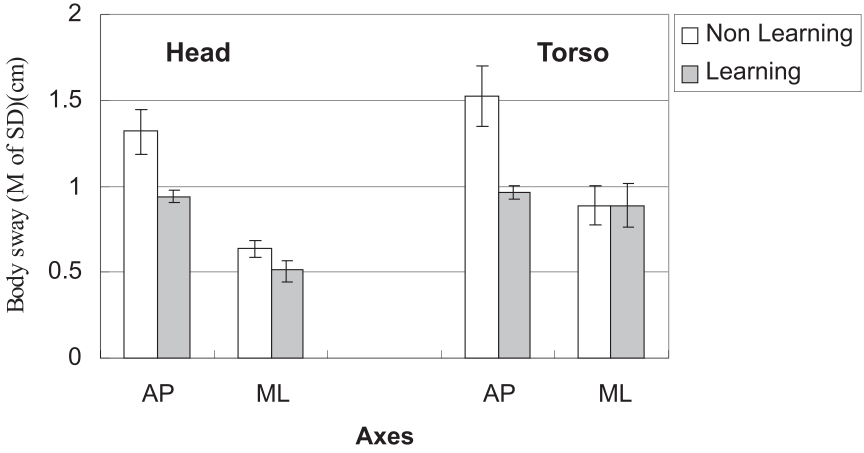


FIGURE 11 Mean postural motion in the control condition, Experiment 2. The error bars are standard error.

was important to perception whenever participants judged maximum sitting height, not just when wearing the blocks. Mark et al. (1990) noted "an observer's activity may be important to the perception of affordances even in commonplace situations where the observer supposedly is familiar with his or her action capabilities, or the actor has had considerable practice or experience" (p. 342).

GENERAL DISCUSSION

In two experiments some of our participants learned about changes in their maximum sitting height. We also found evidence that some participants (at least) learned about their typical maximum sitting height, rather than storing a fixed value in memory. In Experiment 2, our analysis of head and torso motion revealed changes in sway that were related to the judgment task per se; that is, changes that occurred in both participants who learned about their maximum sitting height and those who did not. We also found changes in head and torso motion that were unique to participants who learned about their maximum sitting height during the experimental sessions. These latter results confirm that changes in body sway are related to affordance learning.

Changes in Judgments

Mark (1987; Mark et al., 1990) found that participants learned about changes in their maximum sitting height. We replicated this effect. In each experiment, some of our participants learned about the increase in maximum sitting height caused by the blocks. This finding confirms that people can learn about changes in their action capabilities without practicing the actions in question, and in the absence of feedback about the accuracy of their judgments. This ability suggests that people can obtain information about changes in their action capabilities through some other means.

Changes in action capabilities were not the only spur to learning. Mark et al. (1990) sometimes observed learning even when participants were not wearing the blocks. We replicated this effect as well: In our experiments, some participants learned about their maximum sitting height when they were not wearing the blocks. Consistent with Oudejans et al. (1996), this finding suggests that people's knowledge of their action capabilities may not consist of stored information (i.e., memories) about what they can do. Rather than retaining metric information about action capabilities, we may retain knowledge about how to obtain information about current abilities under local conditions. That we might do this for running ability, as in the study by Oudejans et al., may seem unexceptional, given that the average adult does not spend a great deal of time running, and given that running is an energy-intensive activity in which performance might be influenced by small variations in local conditions (e.g., ground slope or fatigue). But sitting is something that we do every day, often many times each day, and it is something that is relatively undemanding. Our results suggest that people may search out information about their current sitting ability under local conditions, rather than storing metric information about their generic ability. If this is true of an action as mundane and commonplace as sitting, then the role of exploratory perceptual–motor learning may be pervasive (Mark, 1998).

With respect to the generality of our effects, one major limitation of our study and of the studies of Mark (1987; Mark et al., 1990) is that participants were asked to judge (and, hence, to learn about) their maximum sitting capability. Sitting is commonplace, but sitting on very high chairs is much less common. Future research should examine the possibility that people do not store metric information about their preferred sitting height (cf. Stoffregen, Gorday, et al., 1999).

The Direction of Initial Judgment Errors

One clear difference between our study and that of Mark et al. (1990) is in the direction of initial errors in judgments of maximum sitting height. Our judgment data show different direction of initial errors (block condition) from Mark's studies. We do not have an explanation for why the direction of initial errors differs across experiments.

Body Sway and Affordance Learning

The main purpose of our study was to quantify the role of body sway in learning about changes in maximum sitting height. In this, we were modestly successful. The data revealed changes in body sway that were related to improvements in the accuracy of affordance judgments. Changes that were unique to the learning group in the block condition occurred between the control trial and sway while participants were making their first experimental judgment (Figure 10). Changes that were unique to the learning group were also found in the no block condition (Figures 8 and 9). In each case, significant effects were limited to contrasts between motion in the control trial (quiet stance) and during the first judgment. We did not find systematic changes over trials in motion of the head or torso that were related to increasing judgment accuracy. This failure might suggest that sway plays a small role in affordance learning. Alternatively, the gradual changes in affordance judgments may not depend on gradual changes in body motion. For example, changes in perceptual judgments might gradually improve through the repetition or continuous deployment of a fixed or stable pattern of motion. Another possibility is that there are gradual changes in motion that parallel changes in perceptual judgments, but that the changes do not alter the spatial magnitude of motion of the head or torso. Upright stance is a complex, multijoint activity exhibiting structure in a large number of parameters, including not only spatial magnitude but also temporal magnitude (e.g., time derivatives of position), coordination of movement around different joints (e.g., hip–ankle relative phase; Bardy et al., 1999), recurrence (e.g., Riley, Balasubramaniam, & Turvey, 1999), and so on. Patterns of body motion that enable learning about maximum sitting height might exist in any of these.

Postural Stabilization of Affordance Perception

The most general result of our analysis of body sway was that motion of the head in the AP axis was tuned to the suprapostural task in which participants were engaged, extending a result that has been reported in several recent studies of posture (e.g., Stoffregen et al., 2000; Stoffregen, Smart, et al., 1999; Wulf et al., 2003). When participants were engaged in judging their maximum sitting height, they reduced their AP head motion relative to adjacent periods of time when they were not making these judgments. Moreover, the significant interaction for head motion in the AP axis between judgment intervals and trials reveals that participants selectively increased their head motion, over time, during interjudgment intervals, while maintaining a stable level of motion across trials while making judgments. This interaction means that in the later trials, AP motion of the head went through cyclical increases and decreases as participants made judgments and then waited for the next judgment trial to begin. The nature of the interaction resembles a finding by Pagulayan, Hayes, and Stoffregen (2001) in the context of hard and easy visual signal detection tasks. They asked standing participants to perform hard or easy visual tasks (signal detection). Pagulayan et al. found that postural sway was stable during performance of the hard signal detection task, but that sway tended to increase over trials during performance of the easy task. Similarly, our participants appear to have learned, over the course of 24 judgments (and 23 corresponding interjudgment intervals) that they could tolerate increased head motion when they were not making judgments but needed to maintain a constant (lower) level of variability during trials. This interaction appears to constitute postural learning. Specifically, it appears that our participants learned, over trials, that different types of postural control were optimal during judgments and between judgments. From the perspective of our original hypotheses, it is unfortunate that this postural learning was not related to participants' ability to learn about their maximum sitting height. Nevertheless, postural learning did occur, and was related to the nature of the suprapostural tasks in which participants were engaged.

In addition, the online modulation of sway variability (from judgment intervals to interjudgment intervals) resembles an effect reported by Stoffregen et al. (2000). They asked standing participants to switch their focus from nearby or distant targets (or the reverse) within trials. These shifts in the distance of fixation yielded significant effects on the variability of postural sway, indicating that participants modulated their postural control online as a function of fixation distance.

The Functions of Body Sway

Our sway results support the general contention that body sway is not (or is not exclusively) noise (i.e., random, uncontrolled). Riccio (1993) argued that oscillation of the head and body in ordinary sway generates information about the qualitative dynamics of the animal–environment interaction. Given that this information is made available by sway, and given that the information is relevant to performance of at least some perception–action tasks, Riccio argued that people should be sensitive to the information, on a task-specific basis. Recent studies (e.g., Riley et al., 1997; Riley, Stoffregen, et al., 1999) have shown that the spatiotemporal structure of sway differs in familiar and unfamiliar postures (upright stance vs. leaning) and that sway in unfamiliar postures has spatiotemporal asymmetries that make available information about the limits of controllable sway while at the same time reducing the overall amount of effort needed to maintain upright stance. These findings suggest (but do not confirm) the integration of at least two functions in body sway, maintenance of stance and the generation of information about balance dynamics. Our results, together with those of Mark et al. (1990), suggest an additional (or broader) function, specifically, the use of sway to generate information about nonpostural dynamics of the animal–environment interaction.

In our study, sway was related to improvements in affordance judgments even in the no block condition. This finding supports the idea that sway is routinely modulated in task-specific manner to reveal information about the animal–environment interaction. We do not see body sway as being unique in this regard. It seems likely that nearly all movement has (or can have) exploratory characteristics.

Exploratory Movement and Affordance Learning

Our findings, together with those of Mark et al. (1990) and Oudejans et al. (1996), suggest that affordance learning, and affordance perception in general, may routinely depend on exploratory movement, rather than on memories of action capabilities. Oudejans et al. found that a single running step was sufficient to improve judgment accuracy, as compared to a condition in which participants stood still. When standing still, participants were engaged in the control of postural sway. This suggests that information made available by body sway was not sufficient for participants to detect their ball catching ability. This contrasts with the finding that body sway is sufficient for learning about maximum sitting height (Mark et al.). Taken together, these findings appear to imply that learning about different types of affordance depends on different types of exploratory movements, as suggested by Mark et al. This idea, in turn, suggests that an important aspect of learning to perceive affordances is learning which particular movements are optimal for generation and pickup of information about the particular affordance that one wishes to perceive. The task-specific deployment of different exploratory movements has been observed in infants' perception of affordances for locomotion (e.g., Adolph, 2002). Other research has demonstrated that refined sensitivity to changing action capabilities exists in the elderly (Konczak, Meeuwsen, & Cress, 1992). It seems credible to suggest that the elderly use skilled exploratory movement to monitor the diminishment of action capabilities that occurs with aging (this is a testable hypothesis). We can surmise that a significant aspect of affordance learning throughout the lifespan is the skill of differentiating the exploratory movements that are appropriate for a given situation.

Future Research

At a general level, our results underscore the need for further research on the role of exploratory activity in the perception and learning of affordances. Here, we highlight two areas of research that, in our judgment, would be specially rewarding.

If affordance perception depends on exploratory activity, and if exploratory activity is a task-specific skill, then we would expect to find different types of exploratory activity in novices, that is, in pers*ons* who have little experience at perceiving a particular affordance. In this respect, judgments of maximum sitting height are not ideal, given that all healthy adults are—presumably—experts. Few studies have quantified the fine details of perception action coupling among people who credibly could be considered to be novices (e.g., Smith, Flach, Dittman, & Stanard, 2001). Two limitations of this research, in this context, are that it has rarely considered exploratory activity and has not been conducted in the context of affordance perception (Stoffregen, 2000). It would be interesting to quantify exploratory activity in healthy adults who are asked to perceive an affordance that is new to them; that is, to perceive their ability to perform an act that they have not previously performed.

The hypothesis that exploratory activity is task specific also suggests a search for different types of exploratory activity in perceiving different types of affordances. There is a need for quantitative studies directly comparing exploratory actions used in perceiving distinct affordances; to date, such research has been solely qualitative (e.g., Mark, 1987; Warren & Whang, 1987). We might even expect to find different exploratory actions being deployed in the service of different types of judgments about a single action, such as maximum versus preferred riser height in stair climbing (Stoffregen, Gorday, et al., 1999; Warren, 1984; cf. Riley et al., 2002), or preferred distance for different types of reaches (cf. Mark et al., 1997). Differences in exploratory activity between judgments of maximum and preferred values for a given act would suggest that exploration is precisely tuned to particular types of information, as has been documented in exploratory manual wielding (Riley et al., 2002; cf. Turvey, 1990).

CONCLUSION

We asked participants to judge their maximum sitting height while standing normally or while standing on blocks that increased their maximum sitting height. Some participants learned (over the course of 12 judgment trials) about how the blocks changed their capabilities, but we also found that some participants learned about their unmanipulated maximum sitting height in the normal stance condition. We also recorded motion of the head and torso. We found several changes in postural motion related to the act of judging maximum sitting height (as contrasted with intervals between judgments, and with the quiet stance control trial). We also found changes in postural motion unique to those participants who learned about their maximum sitting height during the experimental session. Our results highlight the need for research on affordances in the context of perception–action, not solely in the context of judgments of category boundaries (Stoffregen, 2000).

ACKNOWLEDGMENTS

Preparation of this article was supported by *Enactive Interfaces*, a network of excellence (IST contract 002114) of the Commission of the European Community, and by the National Science Foundation (BCS-0236627). We thank Masato Sasaki and Michael Riley for helpful discussions relating to this work.

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