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Perceiving What Is Reachable: Systematic Errors in the Perception of an Affordance

Philippe Rochat and Maryjane Wraga
Emory University

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Emory University
Atlanta, Georgia 30322

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Correspondence and requests for reprints should be sent to Philippe Rochat, Department of Psychology, Emory University, Atlanta, GA 30322.

Abstract

The significance of perceptual errors in theories of perception that emphasize both direct and indirect processes is discussed. It is argued that perception is best described as direct and veridical when it is tightly coupled with action, and as indirect and error prone in other contexts. Errors in the perception of affordances occur naturally in the course of skill learning and development, as well as in unusually restrictive postural conditions. A model of the postural determinants of perceived reachability is proposed to account for the systematic overestimate of the distance at which an object is perceived as reachable. The model states that these errors are due to a mapping of the limits of prehensile space onto the perceived limits of maximum stretchability with a full, unconstrained body engagement. In support of the model, five experiments on the perceived reachability of both static and dynamic objects are reported. It is tentatively concluded that the mental imagery of action is grounded and calibrated in reference to unconstrained, multiple skeletal degrees of freedom. Accordingly, this calibration is a source of systematic error in the perception of what is reachable.

PERCEIVING WHAT IS REACHABLE:
Systematic Errors in the Perception of an Affordance

The question of how actors situate themselves in the environment is a fundamental problem of perception. When moving and acting, perceivers constantly monitor their situation in relation to objects and obstacles in the environment. Reaching is typical of a basic act requiring such monitoring. In particular, it necessitates the detection of information specifying an object's possibilities for manual action: the object's affordance for touching and eventually grasping. Recent research shows that judgments of the limits of prehensile space tend to be overestimated systematically (Carello, Grosofsky, Reichel, Solomon, & Turvey, 1989; Bootsma, Bakker, Snippenberg, & Tdlohreg, 1992; Heft, 1993). How do we account for this systematic error, and what does it tell us about the determinants of perceived reachability? The aim of this paper is to address these questions.

The Validity of Perceptual Errors

A great number of empirical observations that support general theories of perception pertain to perceptual errors. Theories of perception have traditionally used phenomena associated with ambiguous figures, geometric illusions, and over- and undercompensations in perceptual constancy as paradigms for the study of perception. The theoretical motivation underlying such a trend is the assumption that perception is fundamentally nonveridical and indirect.

In contrast, it is sometimes thought that the ecological theory of J.J. Gibson (1966; 1979) considers perceptual errors as marginal and irrelevant phenomena. In Gibson's radically new approach, perception is viewed as fundamentally direct (bottom up) and veridical, not requiring the intervention of higher cognitive processes; hence, not associated with any kind of reconstruction. Gibson postulates the existence of laws of perceptual information that are general and exact. Invariant information is readily available in the ambient optic array which reflects the way the environment is structured (Gibson, 1979). According to Gibson (1966), perceptual systems have evolved to pick up this information *directly,* without the mediation of any higher reconstruction process. Within this theoretical framework, perceptual errors and the problem of misperception are viewed as exceptions to the ecological optics, the expression of a "...failure to pick up *all* the available information, the inexhaustible reservoir that lies open to further scrutiny" (Gibson, 1979, p. 243). Thus, perceptual errors come from ecological contradiction, perceptual misinformation, and, typically, from the experience of frozen optical information in pictorial displays.

A further distinction of Gibson's ecological approach that is linked to the idea that perception is direct and veridical, is an emphasis on the tight coupling between perception and action. According to Gibson, what is perceived are meaningful aspects of the environment and in particular its resources for action. Accordingly, perception is primarily oriented towards picking up stimulus information that specifies possibilities for action offered by the environment to the perceiver/actor, its *affordances*: whether for example an object is reachable, eatable, or breakable. In Gibson's own terms, affordances are what the environment "...offers to the animal, what it provides or furnishes, either for good or ill." (Gibson, 1979; p. 127). Again, the perception of affordances is direct and does not require the mediation of any thought processes. Of all theories of perception, the theory of affordances is unique in its emphasis on the tight functional coupling between perception and action, leaving little room for perceptual errors.

If perception is veridical and perceptual errors are rare, it does not mean that these errors are insignificant or invalid within an ecological framework. At a basic level of survival and in many risky situations such as driving a car or rock climbing, perceptual errors can be fatal. Furthermore, perceptual errors are of a great theoretical interest in the context of skill learning and development. The progressive attunement of perception coupled with the overcoming of misperception play a central role in the progress of expert action systems. Perceptual learning and development is indeed based on the progressive detection and differentiation of invariant information specifying objects and surfaces (Gibson, 1969). Associated with this process is an improved ability to detect affordances for action (Gibson, 1982; Gibson, Riccio, Schmuckler, Stoffregen, Rosenberg, & Taormina, 1987). For example, learning to walk by babies implies exploration and groping--in other words, falling and misperceiving affordances. Moreover, airplane pilots improve their aircraft landing skills in reduced visibility conditions by crashing in the safe environment of the flight simulator. Finally, at a methodological level, and when perceptual errors are systematic, hence robust phenomena, they can be used as dependent measure to investigate determinants of perception. The experiments presented below are examples of such an approach.

Although animals appear to possess the ability of detecting the affordances of their environment, the misperception of affordances is fairly common, sometimes dramatic. It is not uncommon to witness a squirrel misperceiving the affordance of a branch and falling from a tree. Radiography of the bones of free-ranging, highly arboreal orang-utans, gibbons, and capuchin monkeys reveals multiple bone fractures (Shultz, 1969). For example, Shultz reports that out of 260 skeletons of wild adult gibbons, 33% show at least one healed fracture. These fractures are probably due to falls as in the much more terrestrial macaques and baboons, such instances of broken bones are very rare (Shultz, ibid). Recently, Adolph, Gibson, and Eppler (1990, 1993) studied human infants invited by their parent to either crawl or walk down a steep slope. Young crawlers, as well as young walkers, appear to engage straight down the slope, risking a fall. In contrast, experienced crawlers, as well as experienced walkers demonstrate more caution. They turn their bodies around first, and then slide down the slope. These findings indicate that at different stages of locomotor development, infants show a different appreciation of the affordances of the surface on which they locomote (i.e., its relative slant). They learn to respond appropriately to the affordances of the terrain. This learning entails periods of misperception and progressive adjustments, and requires constant monitoring by parents and caregivers.

Systematic Errors in the Perception of What Is Reachable

Systematic errors in the perception of affordances do exist and appear to persist despite learning and development. Systematic errors, and in particular underestimates, are reported in research on the perceptual discrimination of the height at which a stool affords sitting-on (Mark, 1987), and of the height at which an obstacle affords stepping-onto or stepping-over for children (Pufall & Dunbar, 1992). The results reported by Pufall and Dunbar show that the underestimation of the critical upper limit of the stepping affordance tends to increase up to 10% as a function of the distance separating the observer and the obstacle (1, 3.5, or 7 meters). These data indicate that although body-scaled information and the detection of objects' affordances might be perceived directly (Gibson, 1979), they are commonly associated with systematic errors of judgment. In general, these systematic errors of judgment remain unexplained. The specific aim of the present experiments is to account for some of these errors, in particular errors in perceived reachability, and to capture their underlying mechanism.

Recent research shows that the perceived critical limits of what is reachable, although body-scaled, are associated with systematic biases in judgment. Carello, Grosofsky, Reichel, Solomon, and Turvey (1989) reported a systematic overestimation in adults' perceptual judgments of the distance at which an object was reachable. In different studies varying subjects' reaching space and the way they were permitted to reach, Carello and collaborators reported overestimates produced in some experimental situations by over 90% of the subjects.

Bootsma, Bakker, Snippenberg, and Tdlohreg (1992) reported analogous overestimates in reachability judgments provided by adult subjects for a dynamic object swinging at various distances in front of them. Bootsma et al. found an average of 8.6%

overestimation in reachability judgments. Because of their view of perception as veridical, Bootsma et al. minimized this systematic overestimation. Based on the fact that the standard deviation was relatively small, they concluded that "...the reachability of passing objects can be perceived quite accurately." (Bootsma et al., 1992, p. 13). However, it is unclear what these authors mean by "quite accurately," and whether they are suggesting that the perception of this affordance is "almost" veridical.

Errors in the perception of what is reachable are certainly not due to a lack of learning opportunity, considering that from the onset of development objects are gauged for what they afford for manual action. Newborns tend to reach toward an object moving closely in front of them (Hofsten, 1982). From 2 months of age, infants systematically start using their hands, mouth, and eyes to explore novel objects (Rochat, 1989), and by 4 months, they display systematic and successful attempts to reach and grasp objects they see (Piaget, 1952; Hofsten & Linhagen, 1979; Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993), or objects they hear sounding in the dark (Clifton, Rochat, Litovsky, & Perris, 1991). From the onset of development, reaching behavior appears to be determined by the appreciation of a critical zone or distance at which the object is reachable (Field, 1976; Clifton, Perris, & Bullinger, 1991; Yonas & Hartman, 1993). In a recent study, Rochat & Goubet (in press) presented 4- to 7-month-old infants with an object placed either within reach, at the limit, or only 4 inches outside the limit of their prehensile space. They found a marked decrease in the frequency of reach attempts for the object when placed either at the limit of prehensile space, or out of reach. Interestingly, infants appear to calibrate their overt judgment of what is reachable to their relative ability to sit independently (Rochat & Goubet, 1993), or to lean forward with their trunk (Yonas & Hartman, 1993). These abilities apparently contribute to the determination of the limits of prehensile space.

These observations suggest that the perception of what objects afford for action is manifest from the onset of development. Infants seem to scale their perception of environmental resources to their own developing abilities and degrees of behavioral freedom. Children from 3 years of age were shown to scale their perception of what is reachable for themselves and for others (Rochat, in press). When asked to judge what is reachable for an adult, they systematically and accurately attributed more reachability to the adult compared to themselves. Furthermore, they displayed accuracy when asked to judge what is reachable for themselves, or for an adult, placed in an "imaginary" posture. In particular, young children's reachability judgments were commensurate to the actual reachability measures when asked to *imagine* either themselves, or the adult experimenter, standing on tip-toe under the object-target (Rochat, in press). Thus, young children appear to detect and differentiate objects' affordances for themselves and for others, and are capable of gauging these affordances based on either direct perception or a combination of direct perception and mental imagery. Although children are in general less accurate compared to adults, they also show a significant and systematic overestimation of their own reachability for an object placed on a table in front of them (Rochat, in press).

Within an ecological perspective and in an attempt to explain the apparent paradox between direct, veridical perception and the existence of systematic errors in the perception of what is reachable, Heft (1993) introduced the distinction between two types of judgments: *perceptual* and *analytical.* According to Heft, perceptual judgments are based on skilled, unreflective perception-action processes, and are basically accurate. These judgments are not a focal task, but rather are a subsidiary means to achieve a larger goal. In contrast, analytical judgments are viewed as a focal task, and because they are reflective and explicit, they are a source of error. Heft presented the results of a study where subjects were asked to provide reachability judgments either as a focal task (analytical judgments), or in a condition minimizing analytical reflection, where judgments were made as part of a larger focal task (i.e., picking up only reachable pieces to complete a puzzle). The results indicated that in this latter condition, reachability judgments were more conservative, and did not reflect the systematic overestimates of the focal task condition. These results and the theoretical distinction introduced by Heft leave open the question of the exact mechanisms underlying systematic errors in the perception of what is reachable: when they occur, and why they are systematic. If higher analytical processes are responsible for these errors, what is the nature of these processes? The aim of the present research is to address these questions and to test a model on the postural determinants of perceived reachability. This model is proposed to account for the mechanisms underlying systematic overestimates in the perception of what is reachable.

Proposed Model to Account for Systematic Errors in Perceived Reachability

The general assumption of the model is that the perception of what is reachable is calibrated in reference to more than one degree of behavioral freedom and the unconstrained effectivities of an actor. Effectivities refer to the body's potential for action (Turvey & Shaw, 1978). In perceiving the critical limit of an object's reachability, the perceiver/actor detects this limit on the basis of an unrestricted, whole-body engagement (i.e., unconstrained effectivities). This general assumption leads to the prediction of a specific bias in the perception of reachability: When in a restricted postural situation with constrained effectivities, the perceiver/actor will tend to systematically overestimate the limits of prehensile space, which, according to the model, are calibrated in reference to unconstrained degrees of behavioral freedom. Hence, the model predicts systematic overestimation of perceived reachability in constrained postural conditions. These restrictive postural conditions that reduce the distance at which an object is reachable tend not to be factored into the perceptual judgment. In general, this overestimation is expected to be commensurate to the amount of postural restriction enforced by the task.

The model emphasizes the role of body posture as a determinant of perceived reachability. In particular, the limits of the sphere of prehension are considered in relation to points of postural reversibility: the points of maximum stretch with hand(s) toward the object-target, without losing balance, or without any major postural adjustment. According to the model, perceived reachability is defined in relation to the calibration and mapping of precise points of postural reversibility. We performed a series of studies to test this model, all of which used the same experimental paradigm. Subjects were asked to judge, in varying postural conditions, the distance at which they thought either a static or dynamic object (i.e., a pitched ball) was just reachable.

General Experimental Paradigm

Subjects were asked to judge the distance at which they could just touch a ball with the tip of the finger of their left or right hand, by extending their arm only, keeping both feet parallel and the rest of the body perpendicular to the ground (experiments 1, 2, 3, and 5), or with a full stretch (see Experiment 4). Aside from Experiment 4, judgments were based on one skeletal degree of freedom (shoulder joint). An important feature of the paradigm is the fact that it required no physical reaching action from the subject, but merely a perceptual judgment with no feedback either from the experimenter or from the outcome of an actual reach. Subjects' reachability judgments were obtained in conditions where the ball was either pitched at various distances from the subject as he or she stood in front, or sideways relative to the ball's trajectory (dynamic condition); or statically presented in front of, or sideways to the subject by the experimenter at various distances (static condition).

EXPERIMENT 1

The first experiment was designed to assess and compare subjects' relative accuracy in perceiving the reachability of a ball in static and dynamic conditions, as well as in relation to three different locations in prehensile space (shoulder height, 30 cm above, and 30 cm below). The specific aim of this experiment was to provide further assessment of the systematic overestimation of perceived reachability reported in the literature and to gather information regarding variations of this overestimation relative to either static or dynamic objects, as well as different locations of the object in prehensile space.

Method

Subjects

Twenty-four subjects, all college students (12 male and 12 female; 23 right-handed, 1 left-handed), participated in the experiment.

Procedure

Subjects stood with their backs against a large blackboard. A horizontal line corresponding to the subject's shoulder height was drawn on the board (middle position) with two parallel lines added, 30 cm above (top position) and 30 cm below (bottom position). In both static and dynamic conditions, balls were presented while subjects stood with their backs against the blackboard. In all conditions, balls were presented to the right and left sides of the subject, in alignment with the three position lines, in either an ascending (away from the subject) or descending (toward the subject) manner. Orders of 3 positions, 2 sides, and 2 manners of presentation were counterbalanced across subjects. Subjects always provided judgments in the static condition first.

Static Condition: Subjects were asked to judge ("yes" or "no" responses) whether or not they could touch a tennis ball presented by the experimenter and moved by hand in increments of 2 cm along the position lines drawn on the blackboard. Subjects stood with their backs against the blackboard, and turned their heads to either the right or left side to see the ball and provide their judgment. A "yes" judgment criterion consisted of being able to touch the ball, with the arm extended and fingers outstretched, using the tip of the middle finger. For each judgment, the experimenter marked the ball's location on the blackboard, and later measured the distance in cm from the subject's saggital midline to the mark.

Dynamic Condition: After judgments in the static condition, subjects stood with their backs against the blackboard, facing a pitching machine. The pitching machine (Ponzo

Aztec Rookie) was located 4 meters away from the blackboard. Subjects stepped 1 meter away from the blackboard so they could not see the ball hitting its surface. The machine pitched soft-pressure tennis balls (Tretorn ST), which targeted fixed locations on the different position lines drawn on the blackboard. The balls passed by the side of the subject at a constant velocity of 6m/sec. Subjects were required to look straight ahead during the pitch. After each pitch, subjects judged whether they thought they could have just touched the ball by raising the arm straight out to the side, maintaining the rest of the body perpendicular to the ground. The pitch was repeated as many times as necessary until subjects were confident in their reachability judgment. In an ascending presentation, the balls were first pitched close (80 cm) to the subject and progressively pitched farther away in steps of approximately 5 cm. In a descending presentation, the balls were first pitched far (300 cm) from the subjects and progressively pitched closer in steps of approximately 5 cm. Once subjects estimated that they could not (ascending condition), or were able to (descending condition) touch the ball, reachability judgments were recorded by measuring the distance from the subject's saggital midline and point of impact of the ball on the blackboard. The balls were dampened slightly before pitching so that an exact trace of their impact was left on the blackboard for measurements.

Scoring and Analysis

Subjects made two successive reachability judgments for each position, in each condition. Following the dynamic condition, the actual limits of the subject's prehensile space were measured for analysis of relative accuracy of their reachability judgments in terms of percent over- or underestimate. For this measurement, subjects were asked to turn around and face the blackboard while holding a piece of chalk in their hands. The chalk was positioned in alignment with the tip of their right or left middle finger. Subjects were required to trace on the blackboard, with arms extended, two arcs from 12 to 6 o'clock. Actual prehensile space was measured in reference to the distance from the subjet's sagittal midline to the intersection of each arc with the three horizontal position lines drawn on the underestimate (perceived/actual x 100). These calculations were based on measurements from the vertical line running through the subject's back heel (saggital midline), to either the middle finger tip (actual), or the ball's location/trajectory (perceived).

Results

As shown in Figure 1, subjects tended to overestimate the limits of their prehensile space.

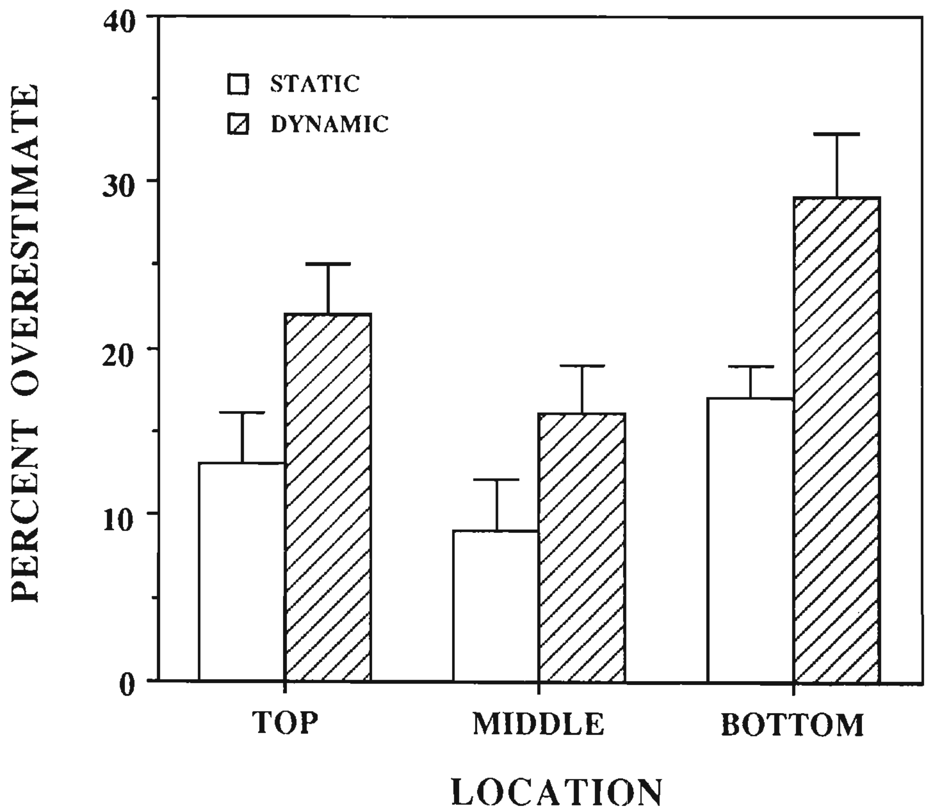

Figure 1: Percent overestimate (perceived / actual x 100) as a function of the three positions of the ball in prehensile space and of the static or dynamic conditions of reachability judgment in Experiment 1.

This trend was significantly greater in the dynamic condition compared to the static condition. The average overestimate in the dynamic condition was 23%, versus 13% in the static condition. A 2 (condition) x 2 (side) x 3 (location) Analysis of Variance with repeated measures yielded a significant main effect of condition, $F(1, 23)=10.54$, $p<.004$, and a significant main effect of position, $F(2, 46)=20.23$, $p<.0001$. The overestimation was significantly higher for the top and bottom ball's position compared to the middle position. No significant effect of side and no interactions were found.

Discussion

The results of the first experiment confirm the existence of a systematic overestimate of perceived reachability. It demonstrates further that this overestimate is significantly greater for a dynamic compared to a static object. In addition, it shows that this overestimate depends on the location of the object in prehensile space. The overestimate increases when above or below subjects' shoulder height.

The fact that subjects had to imagine a reach to the side because they were not positioned in the fronto-parallel plane relative to the ball's trajectory as it passed by could possibly account for the systematic errors in perceived reachability. To provide their judgments, subjects either had to turn their head sideways (static condition), or use their peripheral vision (dynamic condition). Thus, subjects were placed in an awkward, unusual posture to plan a reach. This unusual posture might have determined the observed misperception. Experiment 2 was performed to control for this possibility and to test the generality of the observed overestimate in a situation where subjects were placed in the fronto-parallel plane relative to the ball's trajectory. This situation was conceived as more familiar, and possibly associated with less error because it entails the imaging of a forward reach in a less awkward posture.

EXPERIMENT 2

As in Experiment 1, the second experiment was designed to assess and compare subjects' perceived reachability of a ball in static and dynamic conditions, and relative to three different locations in prehensile space (shoulder height, 30 cm above, and 30 cm below), but in a situation where subjects were situated differently in relation to the ball's trajectory.

Method

Subjects

Twenty-four subjects, all college students (12 male and 12 female; 23 right-handed, 1 left-handed), participated in the experiment.

Procedure

The same general procedure of Experiment 1 was replicated in the second experiment, with the same counterbalancing of variables (see above). However, two procedural modifications were introduced: 1) subjects stood sideways in relation to the blackboard and the pitching machine, and 2) subjects provided their reachability estimates by moving closer to or away from the ball, which was presented or pitched at a constant location in space.

Static Condition: Subjects stood sideways to the blackboard, facing the ball, which was held by the Experimenter at a fixed location corresponding to the shoulder, 30cm-above, or 30cm-below positions. Subjects were asked to judge whether or not they could touch the tennis ball by moving themselves either toward (descending), or away from (ascending) the ball. A "yes" criterion consisted of being able to touch the ball with the arm closer to the blackboard extended and fingers outstretched, using the tip of the middle finger. Movement in either direction was achieved by having subjects take half steps between each trial. Once situated at the perceived reaching distance, the experimenter recorded the judgment by measuring in centimeters the distance from the most outer part of the ball to the subject's saggital midline.

Dynamic Condition: After judgments in the static condition, subjects stood sideways to the blackboard and the pitching machine. The pitching machine (Ponzo Aztec Rookie) was located 4 meters away from the blackboard. Subjects stood 2 meters from the blackboard. The machine pitched soft-pressure tennis balls (Tretorn ST), which targeted fixed locations on the different position lines drawn on the blackboard. The balls crossed the fronto-parallel plan of the subject at a constant velocity of 6m/sec. After each pitch, subjects were asked to move either closer to (descending) or away from (ascending) the perceived ball's trajectory, up to the location from which they thought they could have just touched the ball by raising the arm. The pitch was repeated as many times as necessary until subjects were confident of the distance in which they situated themselves in relation to the ball's trajectory. In an ascending presentation, subjects were initially placed close to the ball's trajectory (120 cm). They were required to move away to provide their judgments. In a descending presentation, subjects were initially placed far away (300cm) from the ball's trajectory, and were required to move forward to provide their judgments. Once subjects situated themselves in relation to the ball, reachability judgments were recorded by measuring in centimeters on the floor the perpendicular from the ball's trajectory line to the extremity of the subject's saggital midline.

Scoring and Analysis

Subjects made two successive reachability judgments for each position, in each condition. Following the dynamic condition, the actual limits of the subject's prehensile space were measured for further analysis. These limits were mapped by asking subjects to draw an arc on the board while standing sideways to the blackboard, with their right or left arm fully extended, holding a piece of chalk in alignment with the tip of their right or left middle finger. This procedure was carried out for the subject's right and left sides. Differences in relative distance between perceived (judged) reachability and the actual limits of prehensile space at the different target locations on the position lines were converted into percentages of over- or underestimate (perceived/actual x 100). These calculations were based on measurements from the vertical line running through the subject's back heel (saggital midline), to either the middle finger tip (actual), or the ball's location/trajectory (perceived).

Results

As show in Figure 2, subjects tended to overestimate significantly the limits of their prehensile space.

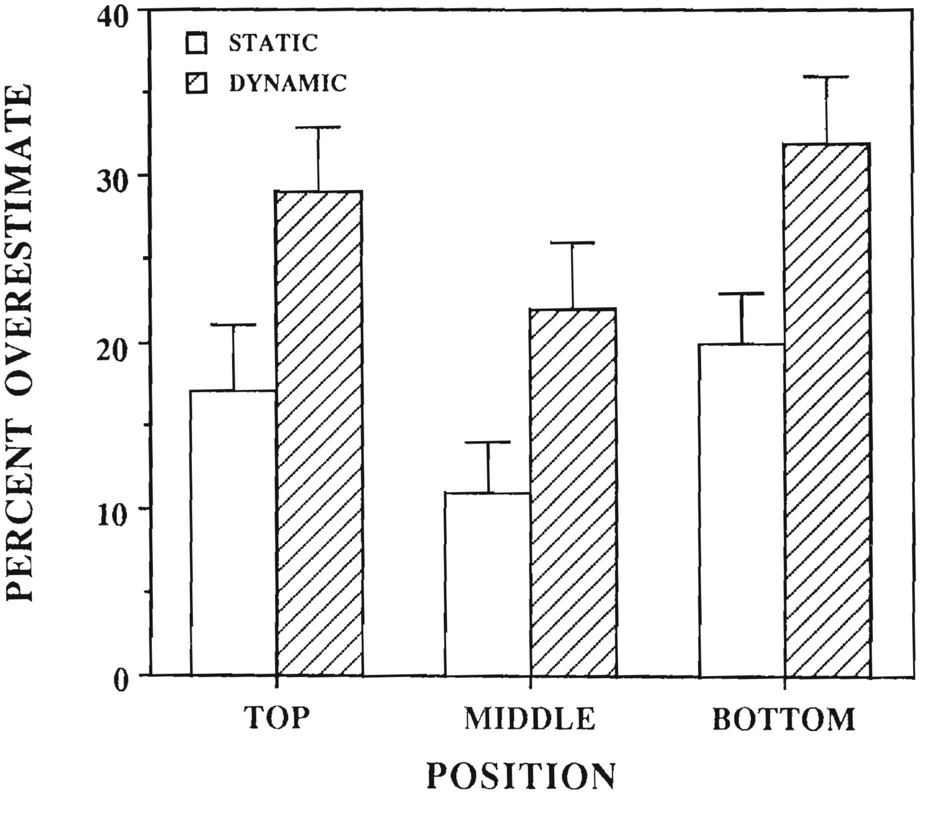

Figure 2: Percent overestimate (perceived / actual x 100) as a function of the three locations of the ball in prehensile space, and of the static or dynamic conditions of reachability judgments in Experiment 2.

This trend was greater in the dynamic condition compared to the static condition (average overestimates of 28% and 16%, respectively). A 2 (condition) x 2 (side) x 3 (location) Analysis of Variance with repeated measures yielded a significant main effect of condition, $F(1,23)=9.89$, $p<.005$, a significant main effect of side, $F(1,23)=76.69$, $p<.0001$, and a significant main effect of position, $F(2,46)=25.72$, $p<.0001$. In both conditions, the overestimate was significantly greater when subjects had to judge reachability for their right hand (blackboard to the subject's right). Furthermore, in both conditions, the overestimate was significantly greater relative to the top and bottom ball's location, compared to the middle location.

Discussion

Apart for the effect of side, these results are remarkably similar to those obtained in Experiment 1. The systematic overestimate of perceived reachability is again significantly greater in the dynamic compared to the static condition. Regarding the effect of side, note that it was marginally significant in Experiment 1 ($p<.09$). In both experiments, subjects tended to overestimate their reachability more when the ball was presented to their right side. This result could be due to the fact that the vast majority of subjects in both experiments were right-handed. Thus, subjects were less conservative in planning their reach to this dominant side.

The proposed model to account for systematic errors of perceived reachability in experiments 1 and 2 states that in general, the source of systematic overestimate comes from a difficulty to perceive and judge reachability based on limited skeletal degrees of freedom. According to the model, subjects tend to perceive and judge an object's reachability in relation to a maximum stretch of the whole body. In other words, the systematic overestimate is linked to the difficulty in accurately judging the ball's reachability within the context of the postural constraints imposed by the task.

The proposed model is supported by the fact that, in both experiments, subjects' overestimates tended to increase significantly when the ball or its trajectory were positioned below their shoulder line (i.e., bottom position). Indeed, in actuality, a whole-body engagement in reaching at the bottom location affords contact with the object at farther distances relative to the vertical line running through the subject's back heel (saggital midline), assuming that subjects take into account at least the constraint of keeping both feet on the ground, and not losing balance. Actual reachability measurements of subjects reaching with a full stretch yield on average a 15% supplemental increase for the bottom position, compared to either the shoulder or top positions. The results support the proposition that the distance at which an object is reachable depends on the perceived limits of maximum stretchability when engaging the whole body, and in particular the perceived *point of postural reversibility*, or the point from which the subject can come back to the initial posture without losing balance (see Figure 3).

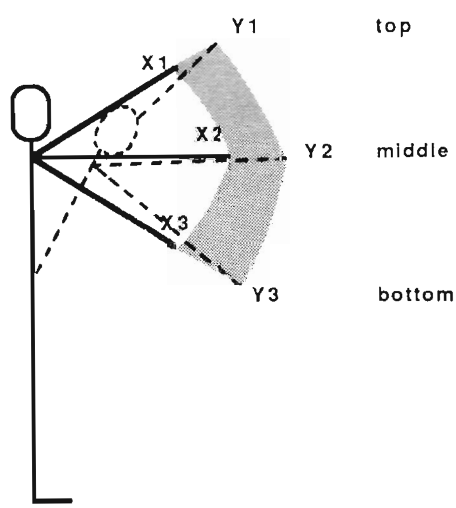

Figure 3. Diagram of the proposed model. X's represent the actual reach for the 3 positions, within the constraints of the task. Y's indicate perceived reachability for the same positions, which corresponds to the point of postural reversibility (dotted lines). The grey area represents the resulting overestimation.

An underlying assumption of the proposed model is that the static and dynamic conditions in our experiments correspond to radically different perceptual contexts. In the dynamic condition, subjects made reachability judgments only *after* the ball had passed before them. In the static condition, subjects provided their judgments while in constant perceptual contact with the ball. The dynamic condition creates a perceptual context that is commonly accompanied by rapid motor responses (i.e., catching), usually performed with a whole-body engagement. In contrast, the constant presence of the ball in the static condition gives subjects more time and opportunity to take into consideration the planning of a reach with one skeletal degree of freedom, hence more opportunity to inhibit their inclination to calibrate the reach with a full stretch. However, this inhibition is only partial because subjects persisted in overestimating the perceived reachability in the static condition as well.

The results of Experiment 2 demonstrate that the systematic error in perceiving what is reachable observed in the first experiment cannot be accounted for by merely the awkward posture of the subjects. The systematic overestimate appears to be pervasive across postural and perceptual contexts. Furthermore, the significant location effect, where errors in perceived reachability were affected by either the top, bottom, or shoulder line location of the object in prehensile space, again provides indirect support to the idea that reachability judgments are based on a full-stretch, whole-body engagement. As mentioned above, reaching with a full stretch at the bottom location of prehensile space (without losing balance and while maintaining both feet parallel to the ground) does indeed afford reachabilty at a farther distance. The third experiment was designed to provide more direct support to the proposed model.

EXPERIMENT 3

To test the viability of the proposed model, subjects in Experiment 3 were asked to provide reachability judgments while wearing various weights attached to one or both of their wrists. The rationale for this experiment was that if the point of postural reversibility plays a role in the determination of perceived reachability, then judgments should vary in relation to the weights attached to the arm engaged in the reaching task. With increasing weight on the reaching arm, the point of postural reversibility is brought back towards the subject's center of mass; thus, the distance at which an object is reachable without losing balance is reduced. According to the model, subjects' judgments should take into account the fact that additional weight on the reaching wrist affords less reachability. Therefore, the model predicts a reduced overestimate in direct proportion to the increased amount of weight on the reaching arm.

Method

Subjects

Fourty-eight college students (37 female and 11 male, 44 right-handed and 4 left-handed) participated in the experiment.

Procedure

Subjects were tested in the same dynamic condition as in Experiment 2, but with the pitching machine to their left side only, and with balls pitched at the middle (shoulder line) position only. Subjects were asked to provide reachability judgments for their right (reaching) arm only. The experimental paradigm and procedure were otherwise identical to Experiment 2, except that subjects were required to wear Softworks exercise weights on one of their wrists while making judgments. They were instructed to vigorously shake the weighted arm several times before beginning judgments of each condition in order to "get a feel" for the amount of weight on the arm. In particular, subjects provided judgments under four conditions:

(1) No weights on either wrists (same as in Experiment 2)

(2) 2 lbs of weights on the right (reaching) wrist and none on the left

(3) 7 lbs of weights on the right (reaching) wrist and none on the left

(4) 7 lbs of weights on the left (nonreaching) wrist and none on the right.

Note that conditions (1) and (4) are control conditions in which the right (reaching) arm is not weighted.

Scoring and Analysis

Subjects provided two successive reachability judgments in each of the four conditions. Judgments were recorded in the same manner as in the dynamic condition of Experiment 2. Manner of presentation (ascending or descending) and order of conditions were counterbalanced across subjects. Judgments were always made relative to the right arm and hand, regardless of which arm was weighted. Because subjects were tested exclusively for the middle position, only the line corresponding to their shoulder height was created on the blackboard. After subjects provided their reachability judgments in all conditions, they were required to stand sideways to the blackboard, and measurements of the actual reachability of their right arm were recorded for further calculations of over- or underestimate (see Experiment 1 & 2, above). Again, these calculations were based on measurements from the vertical line running through the subject's back heel, to either the middle finger tip (actual), or the ball's trajectory at the middle position (perceived).

Results

Similar to the results obtained in both experiments 1 and 2, subjects demonstrated a marked overestimate of the distance at which they thought they could reach and contact the ball (33% overestimate on average). As shown in Figure 4, the results demonstrate a significant effect of the various weight conditions in the direction predicted by the model.

Compared to the experimental conditions where subjects had weights attached to their right (reaching) arm, overestimation was greater in the control conditions (35% in the control conditions versus 31.5% in the experimental conditions on average). Regarding the two experimental conditions, the overestimate was reduced in condition 3, where subjects wore 7 lbs on their right arm, compared to condition 2, where they wore only 2 lbs (30% versus 33% on average.

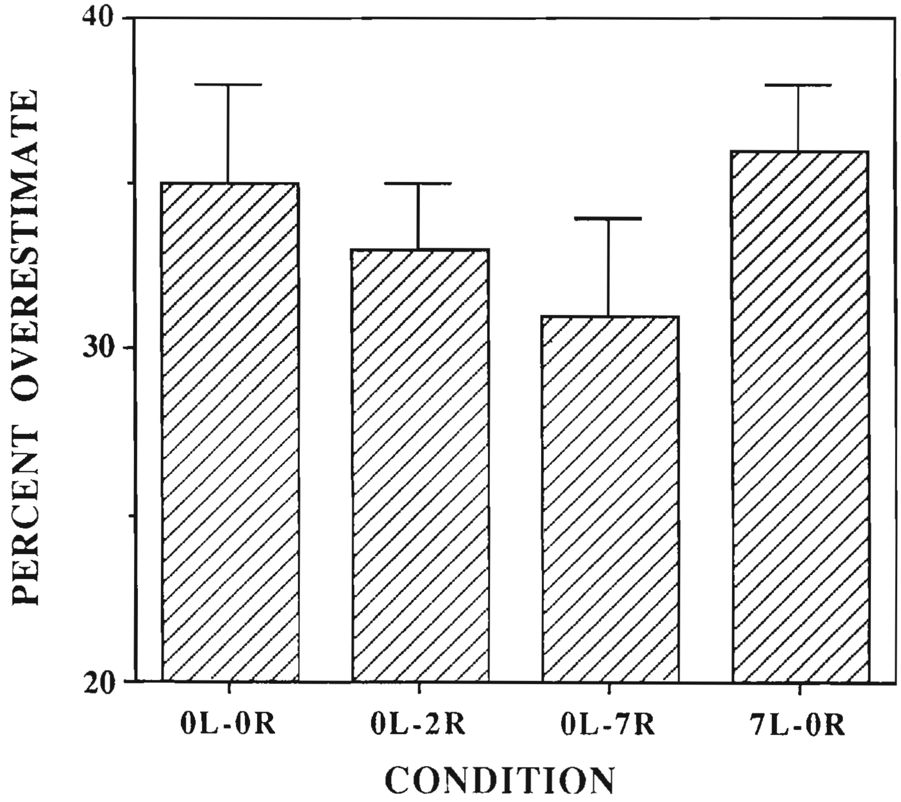

Figure 4: Percent overestimate (perceived / actual x 100) as a function of the four conditions of reachability judgments in Experiment 3: 1) with 0 lb attached to either the left or the right wrist (**0L-0R**); 2) 0 lb to the left and 2 lb to the right (reaching) arm (**0L-2R**); 3) 0 lb to the left and 7 lb to the right (reaching) arm (**0L-7R**); and 4) 7 lb to the left and 0 lb to the right (reaching) arm (**7L-0R**).

A one-way ANOVA with repeated measures yielded a significant effect of condition, $F(3,141) = 3.98$ $p < .009$). Analysis of the simple effects showed significant differences between conditions 4, 2, and 3 (for $p < .05$). Out of the 48 tested subjects, 36 showed the overall trend predicted by the model (i.e., overestimate in Condition 1 = Condition 4 > Condition 2 > Condition 3).

Discussion

The results of Experiment 3 provide support for the general idea that the perception of the limits of prehensile space is related to the perceived points of postural reversibility. Errors in perceived reachability, and in particular the systematic overestimate of the maximum distance at which an object is reachable, appear to be mapped onto the points of postural reversibility with a full stretch of the body. Although subjects were asked to provide their judgments while maintaining their body perpendicular to the ground (i.e., one skeletal degree of freedom), they based their judgments on a whole-body engagement. The perceived limit of reachability depends on the limits dictated by the maintenance of balance in a maximum stretch with both feet remaining on the ground, parallel to each other (i.e., the precise point of postural reversibility). As predicted by the model, the results demonstrate that reachability judgments vary in relation to the weights attached to the arm engaged in the reaching task. These results match the fact that with increasing weight, the point of postural reversibility is brought back towards the subject's center of mass, thus reducing the distance at which an object is reachable without losing balance. Subjects' judgments indicated that they took into account the fact that additional weight on the reaching wrist affords less reachability; thus, their systematic overestimate decreased as a function of the weight attached to the reaching arm.

The fourth experiment was designed to provide further direct support to the model. We asked subjects to provide reachability judgments with less postural restrictions (i.e., more than one skeletal degree of freedom). In this experiment, subjects were asked to provide judgments regarding the maximum distance at which they could still contact the pitched ball in a full-stretch, whole-body engagement. According to the model, comparison between actual and perceived reachability in this condition should reveal a marked decrease in the systematic error, since the task requires no postural restriction.

EXPERIMENT 4

Method

Subjects

Twenty college students (15 females and 5 male, 19 right-handed and 1 left-handed) were tested in the same dynamic condition as in Experiment 3.

Procedure

As in Experiment 3, the pitching machine was placed on the subjects' left side only, and balls were pitched at the middle (shoulder line) position only. Subjects provided reachability judgments for their right (reaching) arm only. In contrast to Experiment 3, subjects did not wear any weights while making judgments. They provided reachability judgments in two conditions: (1) with the instruction to maintain their body perpendicular, and feet parallel to the ground (one skeletal degree of freedom), or (2) with the instruction to provide their judgments on the basis of a full-stretch, while keeping both feet on the ground. This was defined as the maximum forward leaning from the hips with arm outstretched while keeping both feet on the ground. Manner of presentation (i.e., ascending vs. descending) and order of conditions were counterbalanced across subjects.

Scoring and Analysis

Subjects provided two successive reachability judgments in each of the two conditions. Judgments were recorded in the same manner as in the dynamic condition of experiments 2 and 3. Judgments were always made relative to the right arm and hand. Because subjects were tested exclusively for the middle position, only the line corresponding to the subjects' shoulder height was created on the blackboard. After subjects provided their reachability judgments in all conditions, they were required to stand sideways to the blackboard, and measurement of the actual reachability of their right arm with either a full-stretch posture, or with only their arm raised and the rest of the body perpendicular to the ground was recorded for further calculation of over- or underestimate (see experiments above). Again, these calculations were based on measurements from the vertical line running through the subject's back heel, to either the middle finger tip (actual), or the ball's trajectory at the middle position (perceived).

Results

As in the first three experiments, in condition 1 (one degree of skeletal freedom) subjects demonstrated a marked overestimate in the distance at which they thought they could reach and contact the ball (28% overestimate on average). In contrast, and as shown in Figure 5, the results demonstrate a significant reduction of the overestimate in condition 2, where subjects had to provide reachability judgments in reference to a full-stretch posture (only 6% overestimate on average). A one-way ANOVA with repeated measures on the percent overestimate (perceived/actual ratio) yielded a highly significant effect of condition, $F(1,19)=114.59$, $p<.0001$.

Discussion

The results of Experiment 4 confirm those of experiment 3 and provide further support to the general idea that the perception of the limits of prehensile space correspond to the perceived points of postural reversibility. As predicted by the proposed model, errors in perceived reachability are markedly reduced when subjects provide their judgments in reference to a full-stretch posture. Errors are significantly reduced but do not completely disappear. Within the context of the proposed model, the residual 6% average of

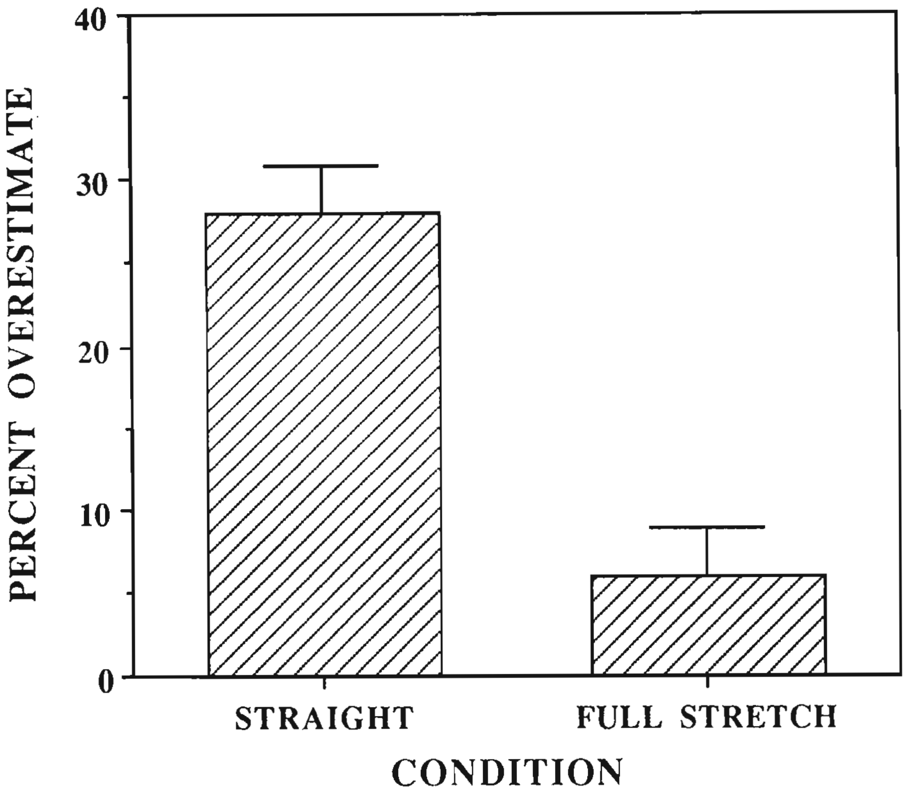

Figure 5: Percent overestimate (perceived / actual x 100) as a function of the two conditions of reachability judgments: 1) while maintaining the body perpendicular and feet on the ground (**STRAIGHT**); 2) With a full stretch while keeping the feet on the ground (**FULL STRETCH**).

overestimate is probably linked to the remaining restriction of keeping both feet on the ground.

The fifth experiment provides a final test of the model in a new static condition. The experimental paradigm used remains basically the same but the context of the judgment task was changed. Subjects were placed in a situation in which the object to be reached was either the image of themselves reflected in a large mirror, or a point on a wall. In addition to this novel context, to test further the proposed model subjects provided their judgments in different postural conditions, which varied their point of postural reversibility when reaching in a full-stretch posture (i.e., standing or kneeling in front of the wall or the mirror). The rationale was that in a kneeling posture, the point of postural reversibility is pushed back compared to a standing posture. Therefore, the model predicts more conservative reachability judgments in the kneeling posture.

EXPERIMENT 5

Method

Subjects

Thirty-six subjects were tested (18 male and 18 female), aged between 18 and 49 years. Subjects were paid to participate in the experiment and were recruited at the Physical Eduction Center of Emory University where they excercised. The experiment was run at the dance studio of the PE Center, using the large mirror covering one of its walls.

Procedure

Subjects stood facing either a large mirror made of twelve panels 10 feet high and 30 feet wide, or a concrete wall. They were instructed to either move away (ascending presentation) or move towards (descending presentation) either their own reflection, or the wall, up to the point where, by *only* raising their right arm forward, perpendicular to their torso, they could either just touched the tip of their reflected right index finger in the mirror, or touched a blue dot glued on the wall at their right shoulder height.

In the mirror condition, the exact meeting point of the subject's right index finger and its reflection corresponded to the actual surface of the mirror. No mention of the mirror surface was made to the subject. Rather, subjects were instructed to situate themselves in relation to their reflection in the mirror. As in Experiments 1-3, subjects were also told that they had to provide their reachability judgments while maintaining their body perpendicular to the ground (one skeletal degree of freedom).

Subjects were tested successively in four conditions: (1) while standing in front of the wall, (2) while kneeling in front of the wall, (3) while standing in front of the mirror, and (4) while kneeling in front of the mirror. In each condition, subjects provided two reachability judgments, which were averaged for later statistical analyses. In the ascending presentation, subjects were first placed close to either the wall or the mirror (80 cm), and in the descending presentation far from it (300 cm). Once subjects situated themselves where they thought they could just touch the wall or their reflected index finger, the experimenter recorded the judgment by measuring in centimeters on the ground the distance from the subject's toes (standing condition), or knees (kneeling condition) to either the wall or the mirror. Manner of presentation (ascending or descending) and order of conditions were counterbalanced across subjects.

Scoring and Analysis

Once subjects provided their judgments in the four conditions, their actual reachability was measured. For this measurement, they were asked to situate themselves either standing or kneeling in front of the mirror. They raised their right arm and just touched the mirror surface, while maintaining the rest of the body perpendicular to the ground. As in the other experiments, the subjects' relative accuracy was assessed based on the ratio of perceived-over-actual reachability.

Results

As in the other four experiments, subjects again demonstrated a tendency to overestimate the distance at which they thought they could reach and contact either their reflected right index finger or the dot on the wall. However, as shown in Figure 6, there is a marked reduction of the overestimate in the kneeling conditions (conditions 1 and 3) compared to the standing conditions (conditions 2 and 4). A 2 (condition) x 2 (posture) ANOVA with repeated measures on the percent overestimate (perceived/actual ratio) yielded a highly significant effect of posture only, $F(1,35)=31.86$, $p<.0001$).

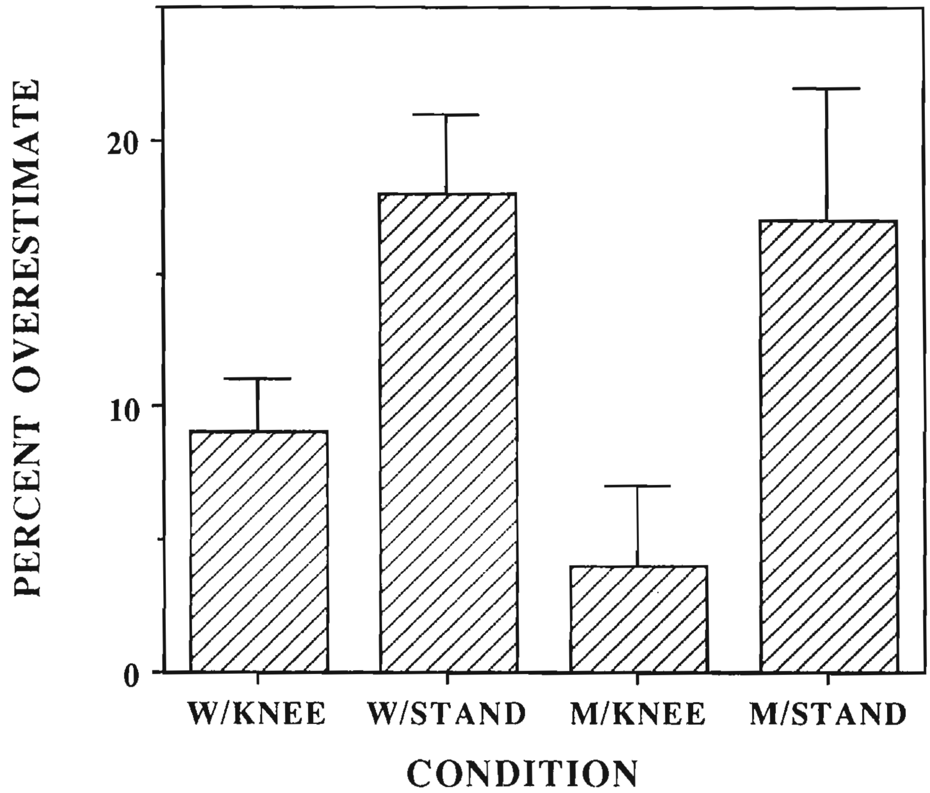

Figure 6: Percent overestimate (perceived / actual X 100) in Experiment 5 as a function of the four conditions: 1) kneeling in front of thewall (**W/KNEE**); 2) standing in front of the wall (**W/STAND**); 3) kneeling in front of the mirror (**M/KNEE**); and 4) standing in front of the mirror (**M/STAND**).

Discussion

The results of Experiment 5 demonstrate that in a frontal static condition, subjects persist in overestimating what they perceive as reachable. These results confirm those of Experiment 1. Futhermore, the particular posture of the subject determines the amount of the systematic error. As predicted by the proposed model, the amount of overestimate is signinficantly reduced in the kneeling posture where the point of postural reversibility is pushed back. These results confirm that perceived reachability is mapped onto the perceived points of postural reversibility in the particular postural condition in which subjects find themselves. Again, although they were asked to judge their reachability based on one skeletal degree of freedom, they tended to respond in reference to a maximum stretch of the body, which varied whether the subject was kneeling or standing. Pilot observations indicated that actual reachability in a standing compared to a kneeling posture increases on average by 16%.

GENERAL DISCUSSION

The results of the five experiments confirm the existence of a systematic error in the perception of what is reachable. In all experiments, for both static and dynamic objects, subjects tended systematically to overestimate their perceived reachability. Aside from simply confirming the existence of such error, the analysis of both magnitude and direction of this error in relation to the various experimental conditions demonstrates that the distance at which an object is perceived as "just reachable" tends to be based on a whole-body engagement. The determination of what is reachable depends on the point of postural reversibility (i.e., the point from which the subject can come back to an initial posture) while reaching out in a full stretch for the object. The systematic error in perceiving the object's reachability is linked to a difficulty in judging its affordance while taking into consideration the postural constraints of maintaining the body perpendicular, with both feet on the ground. Thus, despite the postural constraints dictated by the task, subjects in all five experiments seemed to judge the object's reachability in reference to a maximum stretch of the body, with more than one skeletal degree of freedom, and without losing balance.

What does this tell us about the mechanisms underlying the perception of reachability, and to what extent the systematic error reported in all experiments is perceptual? Of interest is the fact that the reachability overestimation is significantly greater for a dynamic, compared to a static object (see the results of experiments 1 and 2). As already mentioned in the discussion of Experiment 2, the static and dynamic conditions correspond to radically different perceptual contexts. Perception in the dynamic condition is commonly accompanied by rapid motor responses (i.e., catching) and is usually performed with a whole-body engagement. In contrast, in our static condition the ball was always present, which gave subjects more time and opportunity to imagine a reach within the particular constraint of the task (i.e., one skeletal degree of freedom). An obvious conclusion to be drawn is that perceived reachability depends on the context of the task and the type of body engagement a reach would normally entail if performed (i.e., contacting a moving or a static object). In other words, the perception of what is reachable is tightly linked to the way an actual reaching action is normally planned and executed.

The general difficulty of our task resided in requiring the subjects to *imagine* themselves reaching for the object, and not actually to perform the action. Although the task was perceptually based (situating oneself in relation to a perceived object), it required some mental imagery to the extent that there was no performed action: the reachability judgments provided by the subjects referred to an *imagined action*. Because there was no performed action in the context of the tasks, and considering that perception was only supporting imagined reaching, the observed systematic errors correspond to errors in imaging, rather than errors in perceiving and acting. Bootsma (1989) indirectly provides further support for this interpretation, with evidence that the accuracy of perceptual judgments depends on the active involvement of the subject. In different conditions, Bootsma asked subjects either to hit a moving ball with their own arm (natural arm condition), or simply to indicate when they thought the ball was at the point of contact in its trajectory. Subjects' accuracy was significantly greater in the natural arm condition compared to the other. Bootsma concluded that accuracy depends on the tight coupling between perceiving and acting systems. When subjects are asked merely to verbalize whether they think they can do something, the probability of their inaccuracy increases. Based on our findings, this inaccuracy stems from a difficulty in imagining an action outside of a familiar (prototypical) calibration.

The fact that subjects seemed to imagine their reach in the context of a full-stretch, whole-body engagement indicates that there is a rigid format to the mental imagery of action. We did not test for this directly; however, based on Bootsma's (1989) findings, it is probable that within a different task requiring a tight coupling between perception and the planning/execution of an actual reach, postural restrictions would not affect the degree of accuracy in perceiving what is reachable. The embodiment of perceived reachability in the planning and actual execution of a reach act is a source of supplementary visual, proprioceptive, and kinesthetic information that is not available in the imaging of the same act. This information forms the basis of fine adjustments and less error in the detection of the limits of what is reachable.

Among the subjects tested in the five experiments, some were good athletes, and in particular good tennis and baseball players, who are evidently capable of detecting with accuracy the affordance for reaching in the context of their sport. However, these subjects showed as much systematic error when asked about the reachability of moving objects; an action with which they were very familiar. In general, all subjects expressed great surprise upon learning of their systematic overestimation. To test further this hypothesis, future research should compare the performance of subjects required either to verbalize what is reachable with no actual reaching action (as in the present experiments), or to plan and execute an actual reach only when they judge the object is just reachable (e.g., see Heft, 1993).

Considering that detecting objects' affordances is inseparable from an observer's actions, a legitimate question to raise is whether mental imagery is relevant to this process. This question addresses the general issue of the relation between perception, action, and mental imagery. Numerous studies dealing with this issue have demonstrated a perceptual and action analog of mental imagery, whether it refers to the search of an object in a mentally imagined landscape (Kosslyn, 1980; Kerr & Neisser, 1983), the mental rotation of an object (Shepard and Metzler, 1971), or the effects of mental practice on expert action systems (National Research Council, 1991). Our results confirm that there is a perceptual and action analog of mental imagery. Subjects have no difficulty in providing reachability judgments on the basis of an imagined action. However, the perception-action analog of mental imagery appears to be only partial because the imaging of the reaching action is a source of systematic overestimation of the limits of prehensile space.

In conclusion, our experiments demonstrate that systematic errors in the perception of what is reachable come from the fact that it is based on the imaging of a reach with a full stretch of the body, despite the fact that subjects were required to remain perpendicular, with both feet on the ground. This finding suggests that mental imagery is dependent on familiar, prototypical experiences, which are not precisely adjusted to the particular postural constraints imposed by the task and the situation in the environment. Our experiments demonstrate that subjects have a propensity to calibrate the mental imagery of the reach in reference to a full-stretch, whole-body engagement. Thus, the mental imagery of reaching appears to be calibrated in reference to multiple skeletal degrees of freedom. This calibration provides the framework for an obligatory format of imagined action. As illustrated in our experiments, it is also the source of systematic errors in the detection of an affordance.

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