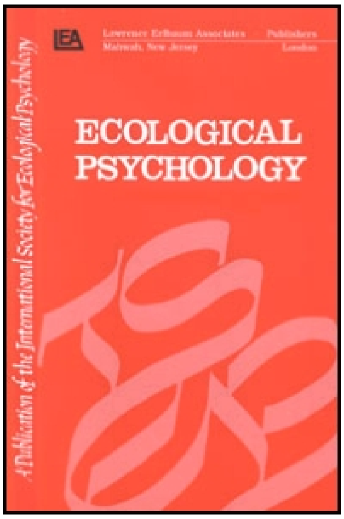
This article was downloaded by: *[University of Minnesota]*
On: *25 August 2010*
Access details: *Access Details: [subscription number 917398484]*
Publisher *Routledge*
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Ecological Psychology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t775653640

Multimodal Perception of Reachability Expressed Through Locomotion

Bruno Mantel[a]; Benoît G. Bardy[a]; Thomas A. Stoffregen[b]
[a] EuroMov, Movement to Health Laboratory, Montpellier-1 University, France [b] School of Kinesiology, University of Minnesota,

Online publication date: 02 August 2010

To cite this Article Mantel, Bruno , Bardy, Benoît G. and Stoffregen, Thomas A.(2010) 'Multimodal Perception of Reachability Expressed Through Locomotion', Ecological Psychology, 22: 3, 192 — 211

To link to this Article: DOI: 10.1080/10407413.2010.496665

URL: http://dx.doi.org/10.1080/10407413.2010.496665

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.informaworld.com/terms-and-conditions-of-access.pdf

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan or sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Ecological Psychology, 22:192–211, 2010
Copyright © Taylor & Francis Group, LLC
ISSN: 1040-7413 print/1532-6969 online
DOI: 10.1080/10407413.2010.496665

Routledge
Taylor & Francis Group

Multimodal Perception of Reachability Expressed Through Locomotion

Bruno Mantel and Benoît G. Bardy
EuroMov, Movement to Health Laboratory
Montpellier-1 University, France

Thomas A. Stoffregen
School of Kinesiology
University of Minnesota

We investigated the information that supports perception of whether an object is within reach using a locomotor task. Participants adjusted their own position relative to a fixed target by stepping or by propelling a wheelchair until they judged it to be within reach. The to-be-reached object was presented in virtual reality. The display of the target was driven in real time as a function of the observer's movement, thus depicting a stationary virtual object at a definite distance only through the relation across optical and nonoptical patterns of stimulation. We asked participants to judge the distance they could reach with their unaided hand or when holding a rod that extended their effective reach. They could see neither their body nor the rod thereby limiting available visual information about "reachability." As expected, our results showed that despite the limited information that was available, participants' locomotor adjustments were influenced by (a) their simulated distance from the target, (b) their arm length, and (c) the presence or absence of the rod. The type of motion (stepping or wheelchair) had little influence. However, judgment accuracy was influenced by participants' initial simulated distance from the target. We compare the performance obtained in our locomotor judgment task with previous studies that have used different methods for measuring perceived reaching-ability. We discuss perceptual information that could have supported performance within the framework of the global array.

Correspondence should be addressed to Bruno Mantel, IBISC Laboratory, Université d'Evry-Val d'Essonne, Boulevard François Mitterand, Evry, France 91000. E-mail: bm@mikmuk.net

To interact successfully with surrounding objects or other persons, it is useful to know how far they are relative to us. Of particular interest is the scaled distance of an object from the perceiver, also known as the absolute or definite egocentric distance (Eriksson, 1974; Pagano & Bingham, 1998). In contrast to relative distance, which involves more than one object and refers to an order of relation (e.g., "A closer than B," "A twice as far as B"), scaled distance refers to an absolute extent whose metric could be either conventional (e.g., centimeters) or functional (e.g., reachable/not reachable). The appropriateness of a given metric depends on the action to be performed and thus, within the framework of scientific research, on the mode of response (e.g., motor, verbal) imposed by the experimenter. Several studies have examined the perception of absolute distance through judgments of whether an object is within reach. In most studies, judgments have been expressed verbally (e.g., yes/no). Because the judgments are verbal, these statements about perceived opportunities for action could be altered by supplementary cognitive processes (e.g., Heft, 1993). In the present experiment, we used an action-based means for reporting perceived egocentric distance. Participants adjusted their own position relative to a target object until they judged it to be within reach. As the target was a virtual object, the participants could not actually touch it. Thus, this task provided motor judgments similar to the verbal judgments commonly used in the literature.

Using that motor task, we addressed the nature of available information that supports the perception of whether an object is reachable. It has been argued that the perception of whether a visible object can be reached is achieved through vision (e.g., Carello, Grosofsky, Reichel, Solomon, and Turvey, 1989), whereas for a sound source it is achieved through audition (e.g., Rosenblum, Wuestefeld, & Anderson, 1996). None of these studies controlled for the potential contribution of other modalities than those manipulated.

The ability to reach an object depends both on its distance away and on the actor's characteristics (e.g., arm length). In this experiment we used a virtual setup to control for available visual information about absolute distance. Although the scale of the scene was not available in optic flow (e.g., Longuet-Higgins, 1986; Stappers, 1992), the absolute distance of the visible object was (in principle) depicted through the higher order relation across optical and nonoptical (e.g., haptic/gravito-inertial) consequences of the perceiver's movement. We also manipulated the actor's reaching capabilities by having participants judge how far they could reach with their hand or with a rod. Participants could move their arm and wield the rod but they could not see their body or the rod. Hence, as for distance, information about whether the visible object could be reached was not available in optics but was (in principle) available within the relation across optical and nonoptical (e.g., haptic) dimensions of the stimulation.

Accordingly, we tested the hypothesis that we could reproduce some of the major findings of the literature on the perception of whether an object is reachable using (a) locomotor judgments in place of verbal ones and (b) an impoverished virtual reality situation in which optic flow alone was ambiguous relative to scaled egocentric distance and to reaching capabilities.

A FUNCTIONAL PERSPECTIVE

One way to evaluate the perception of egocentric distance is to ask participants to judge whether an object is within reach. Reachable distance is a relational property of the animal-environment system (Gibson, 1979/1986; Stoffregen, 2003); it relates a property of the environment (e.g., object position) to a property of an animal (e.g., distance that can be reached). Carello and colleagues (1989) showed that perceived maximum reachable distance differs between short- and long-armed participants when expressed in extrinsic units (i.e., centimeters) but not when expressed in intrinsic units (i.e., as a proportion of arm length). Reaching ability is not influenced solely by arm length (sometimes referred to as a one-degree-of-freedom or 1-*df* reach). We can extend our reach by adding degrees of freedom, for example, by rotating the torso or by leaning forward (e.g., Carello et al., 1989; Mark et al., 1997). Judgments are also known to be sensitive to postural constraints, notably because reaching can challenge the maintenance of balance (Carello et al., 1989; Gabbard, Cordova, & Lee, 2007; Rochat & Wraga, 1997). When provided with rods of different lengths, participants accurately perceive how far they can reach a visible object with the rod even when they cannot see the rod but only wield it (Solomon & Turvey, 1988).

The most common task used in studies to assess reaching-ability comprises yes/no verbal judgments (Carello et al., 1989; Coello et al., 2008; Coello & Iwanow, 2006; Gabbard et al., 2007; Heft, 1993; Mantel, Bardy, & Stoffregen, 2007; Mark et al., 1997; Rochat & Wraga, 1997). In some cases, other methods have been used, including actual reaches (Heft, 1993), remote adjustments of the distance of the distal object (Carello et al., 1989; Solomon & Turvey, 1988), and locomotor judgments (e.g., Bongers, Michaels, & Smitsman, 2004). In general, verbal yes/no judgments yield an overestimation of the actual maximal reaching capabilities (Carello et al., 1989; Coello & Iwanow, 2006; Gabbard et al., 2007; Heft, 1993; Mantel et al., 2007; Mark et al., 1997; Rochat & Wraga, 1997). This overestimation can be accounted for by participants' failure to follow the instruction of judging 1-*df* reaching-ability (Mark et al., 1997; Rochat & Wraga, 1997), by the constraint to maintain a stable posture (Carello et al., 1989; Gabbard et al., 2007), and by restricted information about the target (e.g., with or without a textured background; Coello & Iwanow, 2006).

Performance could also be affected by the response being verbal. For example, Heft (1993) showed that overestimation is almost eliminated when actual reaches are used in place of yes/no verbal judgments. According to Heft, this difference suggests that verbal judgments are more prone to interference from analytical processes than are motor actions. However, the advantage of actual reaches on judgment accuracy may also be due to feedback from touching the reached object, which provides knowledge about the outcome of the action and can improve performance for the remaining trials (e.g., Pagano & Bingham, 1998). Bongers and colleagues (e.g., Bongers, Michaels, et al., 2004; Bongers, Smitsman, & Michaels, 2004) used an alternative task in which participants walked toward an object before reaching it with a rod. The authors analyzed the distance at which participants stopped from the object, that is, the distance from which they felt comfortable to reach the object with the rod. In Bongers, Michaels, et al. (2004), for example, the results showed that stopping distance could be linearly related to the length of the rod, with slopes close to 0.9. As in Heft (1993), the task used in Bongers and colleagues (2004) was more than a motor alternative to verbal judgments because participants also received feedback from touching the object after their walk and were given practice trials before the experiments.

In general, the aforementioned experiments were concerned with the perception *of action boundaries* for prospective control (i.e., movement selection). Verbal and motor tasks have also been compared in experiments focusing on the perception *for online control* of reaching movements (hence using only reachable objects, e.g., Pagano, Grutzmacher, & Jenkins, 2001) or across perception for prospective control and perception for online control (hence using different distance sets for the two tasks, e.g., Coello & Iwanow, 2006; Pagano & Bingham, 1998). Among these studies, Coello & Iwanow compared verbal yes/no judgments with actual reaches, whereas Pagano and colleagues (Pagano & Bingham, 1998; Pagano et al., 2001) compared verbal judgments in arm length units (e.g., "0.65 arm," "0.80 arm") with actual reaches. In general, motor responses have exhibited lower variable error (i.e., greater consistency). For systematic error, no such clear trend emerged. In the absence of physical contact with the target, motor responses appeared either more (Pagano et al., 2001) or less accurate (Coello & Iwanow, 2006) than verbal ones. When feedback was available from contact, motor responses were less accurate than verbal ones, as shown by the slopes of perceived distance as a function of actual distance that were substantially closer to one in the verbal condition (Pagano & Bingham, 1998).

A LOCOMOTOR TASK

With the exception of studies by Bongers, Michaels, et al. (2004) and Bongers, Smitsman, et al. (2004) in previous studies locomotion has been prohibited. In everyday life, however, perceivers will often move toward an object so as to be able to reach it. As in the Bongers and colleagues studies, we used a task in which participants used locomotion to attain a location from which target objects were within reach. Unlike studies of blind walking (e.g., Thomson, 1983), in our experiment the target remained visible as the participant moved toward it. In addition, the required body displacements were small, just as when one wants to attend near space objects to grab them. Contra Bongers, Michaels, et al. (2004) and Bongers, Smitsman, et al. (2004), but in line with previous research that involved yes/no verbal judgments (Carello et al., 1989; Coello & Iwanow, 2006; Gabbard et al., 2007; Heft, 1993; Mantel et al., 2007; Rochat & Wraga, 1997), participants did not receive feedback about the outcome of their judgment during the experiment. Participants did not physically contact the object after locomoting (the virtual object was immaterial), nor did they practice the task prior to experimental trials. By not allowing participants to receive haptic feedback from touching the object, our task provided motor judgments of reachability similar to the verbal yes/no judgments that have been extensively used.

To control for the influence of the means of response (which we differentiate here from the judged property itself) on judged reachability, we tested participants in either of the two principal means of locomotion used by human adults to go to a reachable distance from objects. Half of the participants moved toward the virtual target by rolling in a wheelchair. As most studies on the perception of whether an object is reachable have been conducted with seated participants, using a wheelchair offered some continuity with the literature. On the other hand, one could expect that the novelty of using a wheelchair for our participants would affect their performance. For this reason, the other half of the participants were standing and moved toward the virtual target by stepping.

INFORMATION ABOUT REACHING ABILITY

Carello et al. (1989) proposed that the perception of whether a visible object is reachable is achieved through vision. They argued that the optic array, under the constraint of eyeheight, may provide information about whether an object is within reach. Although this proposal has not been tested experimentally, eyeheight has been shown to influence the perception of other affordances such as the ability to cross an aperture (e.g., Warren & Whang, 1987), to sit on a surface (e.g., Mark, 1987), or to pass under a barrier (e.g., Marcilly & Luyat, 2008). From a formal point of view, the height of an object in the visual field, or more precisely its angular declination below the horizon, provides information about its distance relative to the observer, scaled in terms of eyeheight (at minimum when the object lies on a level ground; e.g., Lee, 1980; Ooi, Wu, & He, 2006; Sedgwick, 1986). If we assume that eyeheight bears a stable relation to other body characteristics such as arm length, then the height of an object in the visual field provides, up to a scaling constant, information about its distance away scaled in terms of arm length. Nevertheless, the optic array does not depend on the anthropometrical eyeheight but on the actual eyeheight, which is contingent on posture. For example, eyeheight is lower (both physically and in the optic array) when seated than when standing (and when seated on a low chair rather than a high stool, etc.). Given that we reach when seated (e.g., Mark et al. 1997) as well as when standing, perception of reachability based on optical eyeheight would appear to require extraoptical information (e.g., learned scaling constants) relating current eyeheight to other body characteristics (e.g., arm length).[1]

The height of an object in the visual field is only one of the many possible sources for perceiving body-scaled or action-scaled information. Presumably, the prospective perception of whether an object is within reach requires relational information about the actor's action capabilities and the egocentric distance of the targeted object. In the previous paragraph we considered the hypothesis that the relation between distance and the body characteristics constraining action may be available in optics. Another possibility is that this relation between distance and body characteristics is available across different ambient energy arrays. In addition, information about absolute distance itself could be relational and available across different ambient energy arrays.

A large body of research has addressed these two sides of the affordance separately. Research on depth perception has identified several structures that can provide information about the distance of an object relative to the perceiver (e.g., Sedgwick, 1986). For example, it has been shown that humans can perceive the absolute egocentric distance of a stationary visible object from the perceptual consequences of their own movement (e.g., Eriksson, 1974; Gogel & Tietz, 1979; Pagano & Bingham, 1998; Panerai, Cornilleau-Pérès, & Droulez, 2002; Peh, Panerai, Droulez, Cornilleau-Pérès, & Cheong, 2002). In these experiments, the dynamic properties of self-generated optic flow were isolated from all other potential visual sources of information. Notably, the object was unfamiliar and did not have any texture. It was presented alone against a uniform background while its size and its height in the visual field were controlled. Because the scale of the scene was not specified in optic flow, the performance observed in these experiments suggests that participants exploited additional—*nonoptical*—information to scale optics (e.g., Bingham & Stassen, 1994; Eriksson, 1974; Nakayama & Loomis, 1974; Panerai et al., 2002; Peh et al., 2002). The functioning of our virtual setup offers a good illustration of this point. The movements of an observer relative to a stationary object generates changes in the direction of the object relative to the point of observation and/or changes in the visual angle subtended by the object and/or changes of perspective. All these optical patterns

---

[1] By contrast, the prospective perception of whether an aperture can be crossed, a surface sat on, or a barrier passed is often achieved while standing.

depend both on the distance (and size) of the object and on the kinematics of the point of observation (Figure 1a) such that a given optical pattern could correspond to an infinite number of combinations of head movements and object distances (Figure 1b).

The side of the affordance pertaining to action capabilities has also been studied. For example, Solomon and Turvey (1988) provided participants with rods of different lengths, materials, and shapes to investigate the role of gravito-inertial stimulation in perceiving how far one can reach with a rod. They showed that participants perceived how far they can reach a *visible* object with a rod that they could wield but *not see*, suggesting that optical and nonoptical information (e.g., haptics) were used concurrently to judge reachability.

From an ecological perspective, these two observations and the related experimental results question the sufficiency of individual energy array formalism. In the first case, optic flow provided information only about relative distance or depth. To perceive the absolute distance of objects, participants needed to use concurrent information about the kinematics of their own motion, which was not available in optic flow (Bingham & Stassen, 1994; Eriksson, 1974; Gibson, Olum, & Rosenblatt, 1955; Nakayama & Loomis, 1974). In the second case, only haptics provided information about rod length and participants needed to use concurrent information about the distance of the visible object to perceive whether it was within rod-reach. In both cases, the information about distance and about reachability were perceived although not specified within individual arrays. On the other hand, these two results can be interpreted in the framework of the global array (Stoffregen & Bardy, 2001), which emphasizes that available perceptual information is not limited to structures within ambient energy arrays but also extends *across* arrays. Regarding absolute distance perception, the participants' movement alters the structure of optic flow but it also creates simultaneous patterns in (at least) the haptic/gravito-inertial stimulation (e.g., of the vestibular system, of the muscles, tendons, joints, and skins of the neck and torso). Accordingly, absolute egocentric distance may have been specified in the global array in patterns extending across optical and nonoptical consequences of the observer's motion (e.g., across optics and haptics/gravito-inertia; Mantel et al., 2007). Similarly, when a participant wields a rod while looking at a target, the haptic stimulation of her or his arm does not occur in isolation. It is accompanied (at least) by concurrent stimulation of her or his visual system and haptic/gravito-inertial stimulation of her or his vestibular system, neck, and torso. Hence, the global array hypothesis can also account for the specification of whether an object is within reach across patterns in optics/haptics specifying absolute distance and patterns in haptics providing information about how far the tool extends beyond the grasping point.

In order to examine whether participants can perceive and exploit information about absolute distance and reachability when these are only available across

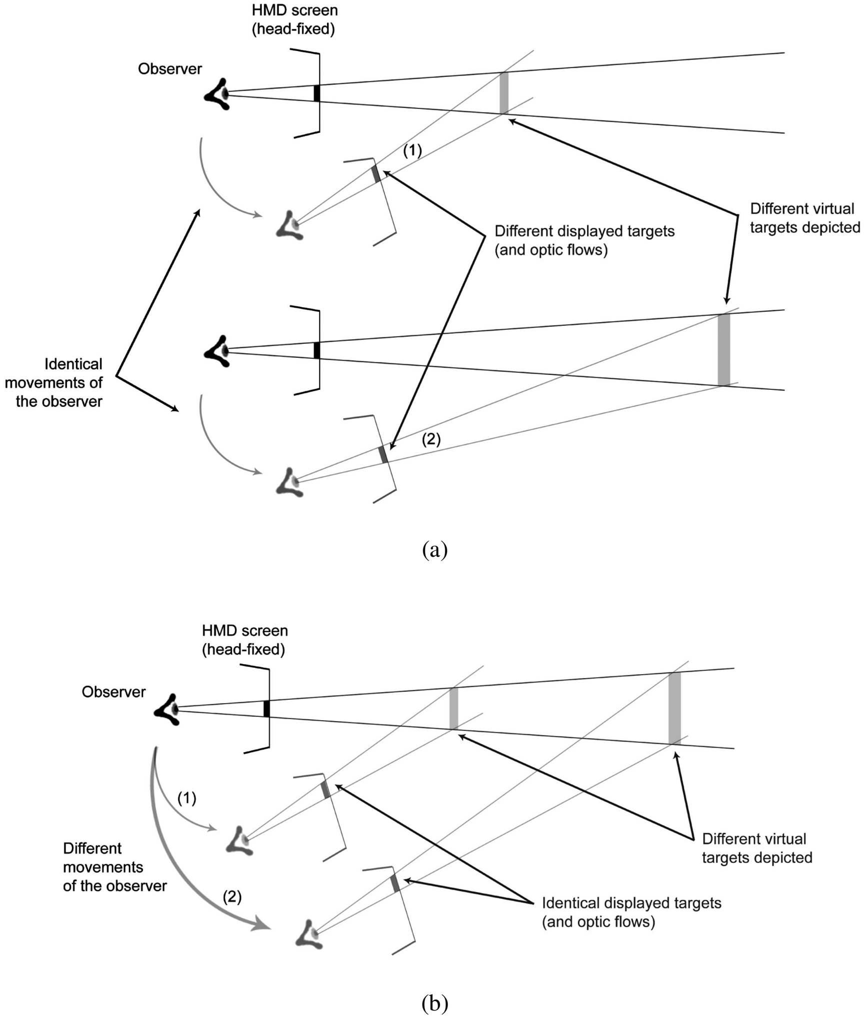


FIGURE 1 Simulating a stationary virtual object for a moving observer. The movement of an observer relative to a stationary object in the real world generates changes in the direction of the object relative to the point of observation and/or changes in the visual angle subtended by the object and/or changes of perspective. To depict a virtual object in a stationary location beyond the head-mounted display (HMD) screen, our setup simulated these optical transformations by updating in real time the displayed target as a function of the observer's movement. Depending on the gain value used, (a) two identical movements of the observer cause different optic flows, thus depicting a stationary virtual target at different distances, or, similarly, (b) different movements of the observer cause two identical optic flows, thus depicting a stationary virtual target at different distances.

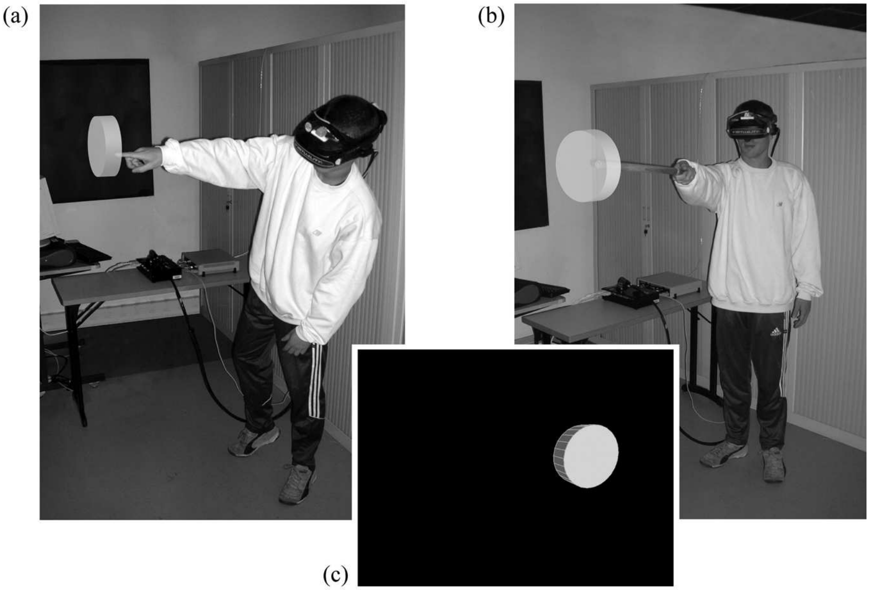


FIGURE 2 Experimental setup. In both the Hand (a) and Rod (b) conditions, the target was displayed on a head-mounted display (HMD), which also occluded the participant's body and the rod. A transparent target has been superimposed on the pictures to illustrate the depicted virtual object. (c) The virtual target was the only visible element on the screen of the HMD (screen caption).

ambient energy arrays, we used a virtual setup (Figure 2) that allowed us to control the available visual information and to ensure that scaled egocentric distance was not specified in the optic flow. In two separate experimental conditions, we asked participants to move toward objects until these were within reach of their hand or within reach of a handheld rod. Because participants could see only what was presented through the head-mounted device, they could not see their arm, the rest of their body, and the rod during the experiment. Hence there was no information about action capabilities in the optic flow. However, both information about scaled egocentric distance and information about this distance in relation to action capabilities was (in principle) available in the global array.

MATERIALS AND METHOD

Twenty-four volunteers, students and faculty members of the University of Montpellier-1, participated (7 females, 17 males). Their ages ranged from 22 to 38 years ($M = 27.3$, $SD = 3.9$) and their heights from 159 to 190 cm

($M = 171.8$, $SD = 7.5$). Their arm length (from the acromion to the tip of the index finger) ranged from 55 to 82 cm ($M = 72.0$, $SD = 5.4$). All had normal or corrected-to-normal vision (6 wore lenses) and all but 1 were naïve about the purpose of the experiment.

We evaluated participants' perception of whether an object was within reach. Participants were asked to move toward a virtual object until they judged they could reach it. We defined reaching as being able to touch the target object with the (self-reported) preferred hand using the arm only, fully extended, without twisting shoulders or leaning forward (i.e., 1-*df* reach).

We used a virtual setup that isolated optic flow from all other possible visual sources of information about distance (e.g., accommodation) and which guaranteed that optic flow was ambiguous relative to scale egocentric distance (see previous section and Figure 1). The virtual target was a 3D coin-like cylinder displayed against a uniform black background (Figure 2c). We covaried simulated target distance and simulated target size such that the target's *angular* size was exactly the same at the beginning of each trial (8°6). The target was presented monocularly in front of the (self-reported) preferred eye. Participants' movements were sampled at 100 Hz using a six-degree-of-freedom electromagnetic sensor (Flock of Birds, Ascension, Burlington, VT) centered just above their eyes. Movements were used in real time to drive the display of the target on the screen of a head-mounted display (HMD; Visette Pro, Cybermind, The Netherlands), such that the target appeared stationary at a fixed position. The distance at which the target was depicted was defined by setting the gain within the relation between head movements and consequent changes in the optical display (Figure 1).

Participants were randomly assigned to either the *Stepping* group, in which they stood erect, or to the *Wheelchair* group, in which they were seated in a wheelchair.[2] In both groups participants were asked to move toward the virtual target until they judged it to be just within reach and then stop. At all times, they could freely explore the situation as long as they wished. Exploration could include reaching movements. However, given that the target was virtual and that participants could not see their own body, they could neither feel nor see their hand in contact with the target. Each participant made judgments with the preferred hand and with a rod held in the preferred hand (Figure 2a, b). The rod was a 62 cm cylinder of wood (3 cm diameter) with tape wound around one end to indicate where it should be grasped. Following previous research (Solomon & Turvey, 1988), participants were allowed to wield the rod but not to see

---

[2] In a control experiment we compared the performance of participants using either this wheelchair or an office chair to verify that accuracy and precision would not be drastically degraded because of the use of a tool with which they were not familiar (the wheelchair). We observed no significant differences between the two chairs.

it. Furthermore, in both reaching modes (hand and rod), the HMD occluded participants' vision such that they could not see their arm or any other part of their body.

The virtual target was presented at seven different simulated distances (separated by 10-cm increments). The range of distances was 80 cm–140 cm for the hand condition (cf. Carello et al., 1989; Coello et al., 2008; Heft, 1993; Mantel et al., 2007; Mark et al., 1997; Rochat & Wraga, 1997; Solomon & Turvey, 1988) and 120 cm–180 cm for the rod condition. For the Stepping group these distances obliged participants to walk at least one or two steps (or several small steps). In each condition, there were five trials at each target distance. Participants were presented blocks of seven trials in a given reaching condition with a rest between blocks. The order of trials and blocks was randomized.

To evaluate judgments, we computed the distance between the participants and the virtual target at the end of each trial. We expressed this *judged* distance in centimeters and as a proportion of the maximum distance over which each participant was able to reach with the hand and with the rod. The *actual* maximum reachable distance (which served as a reference) was measured during real reaching movements performed toward physical objects (i.e., not virtual) after the completion of judgment trials. Following previous studies (e.g., Carello et al., 1989; Coello & Iwanow, 2006; Mark et al., 1997), we assessed judgment accuracy using the mean constant error (*CE*). We quantified precision using the mean coefficient of variation (*CV;* i.e., *SD/M* ratio, e.g., Pagano & Bingham, 1998).

We used an alpha level of .05 for all inferential tests. We report effect size for each test using partial eta square, η_p^2, for analysis of variance (ANOVA), and Cliff's *d* statistic for nonparametric tests (Cliff, 1993). For independent samples, the *d* statistics indicates "the proportion of scores from one population that are higher than those from the other, minus the reverse proportion" (Cliff, 1993, p. 495). Hence, *d* is independent of any assumption relative to the samples' distribution.

RESULTS

In all trials, the participants explored the scene by moving their head in various directions (either by locomoting or simply by tilting their head and/or leaning their torso) before reaching the position they felt adequate. This is illustrated on Figure 3 with four examples of head trajectories (viewed from the top) recorded during the experiment.

Participants from the Stepping group walked a few steps in all trials. We first analyzed judgments expressed in centimeters. The average distances from the target at which participants stopped are plotted on Figure 4 (left) for each

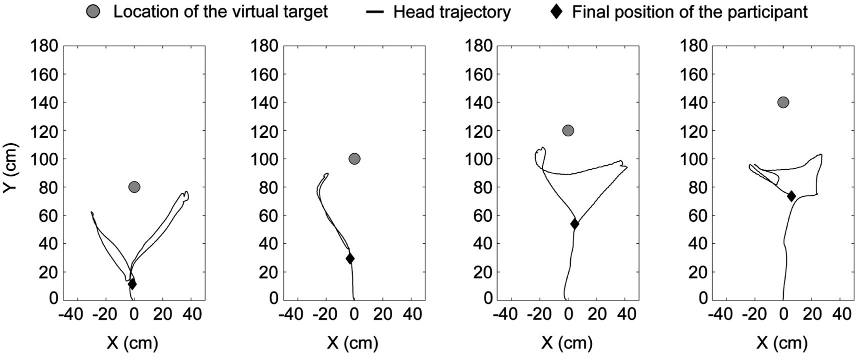


FIGURE 3 Example of head trajectories along the X and Y axes (i.e., viewed from the top). The four graphs correspond to four different trials of the same participant (Wheelchair group #4), within which the virtual target was initially depicted at 80, 100, 120, and 140 cm from the participant (from left to right).

combination of locomotion group and reaching mode. We conducted a Locomotion Group (wheelchair vs. stepping) × Reaching Mode (hand vs. rod) × Distance Type (judged vs. actual) ANOVA on maximum reachable distances. The main effect of Reaching Mode was significant, $F(1,22) = 1{,}016.78$, $p < .001$, $\eta_p^2 = 0.98$. The main effects of Locomotion Group and Distance Type were not significant, $F(1,22) = 1.50$ and $F(1,22) = 0.91$, respectively, each $p > .05$

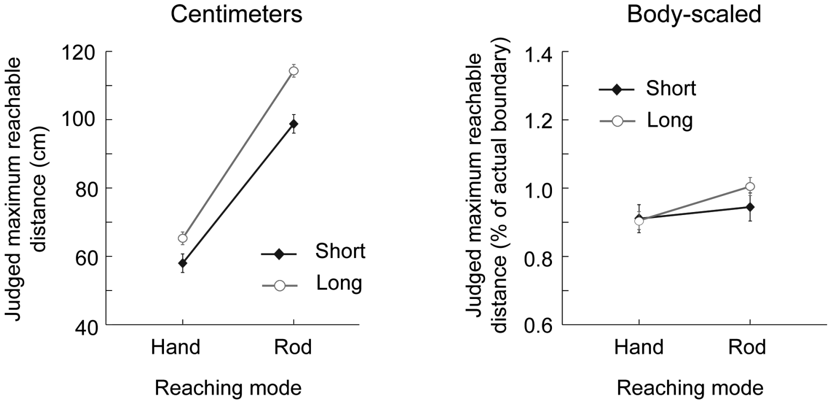


FIGURE 4 Judgment data expressed in extrinsic units (left) and intrinsic units (right). Each panel shows mean judged maximum reach distance in the hand and rod conditions for clusters of participants with long and short actual reaching-abilities. Error bars represent standard errors.

and $\eta_p^2 < 0.07$, as were the interactions, $Fs(1, 22) < 1.23$, *ns*, $\eta_p^2 < 0.06$. The main effect of Reaching Mode indicates, as predicted, that maximum reaches with the rod, averaged over judged and actual, were farther than with the hand. Planned comparison confirmed that this effect was still observed when only judged distances were compared, $F(1, 22)_{\text{Wheelchair}} = 147.62$, $p < .001$, $\eta_p^2 = 0.87$ and $F(1, 22)_{\text{Stepping}} = 110.82$, $p < .001$, $\eta_p^2 = 0.83$. The average differences between judged distances in the two reaching conditions were 48.1 (Wheelchair) and 41.7 cm (Stepping), whereas the differences between actual reachable distances were 41.4 and 41.8 cm. The overall difference between judged and actual maximum reachable distances was not significant (4.6 cm, on average). Planned comparisons confirmed that judged distance did not differ significantly from actual distance in any of the four combinations of Locomotion Group and Reaching Mode, $Fs(1, 11) < 2.37$, *ns*, $\eta_p^2 < 0.10$. When reaching judgments were expressed as a percentage of each participant's actual maximum reach, the difference across hand and rod conditions vanished as revealed by one-way ANOVA, $F(1, 22)_{\text{Wheelchair}} = 1.13$, and $F(1, 22)_{\text{Stepping}} = 0.13$, each $p > .05$ and $\eta_p^2 < 0.05$.

We then compared the perceived maximum reachable distances between participants who could actually reach over long or short distances. We defined Long and Short clusters (6 participants in each) a posteriori by dividing the continuum of actual maximum reachable distance dichotomously. Levene's test revealed nonhomogeneous variances between the pairs of clusters, and so we used Mann-Whitney nonparametric *U* tests to compare the judged distances. When expressed in extrinsic units (cm), the Long and Short clusters differed for both hand and rod conditions, $Z(N = 84)_{\text{Hand}} = 2.00$, $p < .05$, $d = -0.18$ and $Z(N = 84)_{\text{Rod}} = 2.28$, $p < .05$, $d = -0.20$ (Figure 4, left). In other words, participants who could actually reach over longer distances correctly judged that they could reach over longer distance. However, when expressed in intrinsic units (percentage of the actual maximal reachable distance), the differences between Long and Short were not significant, $Z(N = 84)_{\text{Hand}} = 0.09$, *ns*, $d = -0.01$ and $Z(N = 84)_{\text{Rod}} = 0.60$, *ns*, $d = -0.05$ (Figure 4, right).

To investigate whether accuracy differed as a function of target distance, we computed the *CE* for each participant as a function of the initial distance to the target. For both motion groups, the Reaching Mode (hand vs. rod) × Target Distance ANOVA revealed that *CE* was influenced by the initial target distance: in both cases (wheelchair and stepping), *CE* increased as distance increased, $F(6, 66)_{\text{Wheelchair}} = 47.92$, $p < .001$, $\eta_p^2 = 0.81$ and $F(6, 66)_{\text{Stepping}} = 87.00$, $p < .001$, $\eta_p^2 = 0.89$. The increase was greater in the rod than in the hand condition as shown by the significant Reaching Mode × Target Distance interactions, $F(6, 66)_{\text{Wheelchair}} = 3.81$, $p < .005$, $\eta_p^2 = 0.26$ and $F(6, 66)_{\text{Stepping}} = 4.04$, $p < .005$, $\eta_p^2 = 0.27$. The main effects of Reaching Mode were not significant, $F(1, 11)_{\text{Wheelchair}} = 2.81$, *ns*, $\eta_p^2 = 0.20$ and $F(1, 11)_{\text{Stepping}} = 0.00$, *ns*,

TABLE 1
Accuracy and Variability of the Maximal Distance at Which the Virtual Object Was Judged Reachable

			Wheelchair		*Stepping*	
			M	*CI.95*	*M*	*CI.95*
Hand	*CE*	Overall	−4.0	[−8.2; −0.5]	−8.4	[−16.5; −0.5]
		Slope	0.43	[0.31; 0.55]	0.43	[0.35; 0.51]
		R^2	.38	[.25; .51]	.58	[.47; .69]
	CV		.15	[.12; .18]	.17	[.14; .19]
Rod	*CE*	Overall	2.7	[−2.6; 8.0]	−8.5	[−13.7; −3.1]
		Slope	0.64	[0.49; 0.79]	0.57	[0.48; 0.66]
		R^2	.52	[.39; .65]	.61	[.50; .71]
	CV		.12	[.10; .14]	.13	[.11; .16]

Note. Overall constant errors (*CE,* in centimeters), constant error slopes from linear regressions (with coefficient of determination, R^2), and coefficients of variation (*CV*), for the two locomotion groups and the two reaching modes, averaged across participants and presented with their 95% confidence intervals.

$\eta_p^2 = 0.00$. Mann-Whitney nonparametric U tests (used due to nonhomogeneous variances across motion groups) showed that *CE* was significantly greater for the Stepping group than for the Wheelchair group, $Z(N = 168) = 2.42$, $p < .05$, $d = -0.15$. Table 1 presents average *CE* and confidence intervals for each motion group and reaching condition.

To quantify the increase in *CE* with increasing distance, we fitted linear regressions to *CE* as a function of initial target distance for each participant in each reaching condition (Slope and R^2 in Table 1). The slopes for the hand condition were similar in the Wheelchair and in the Stepping groups, whereas for rod condition the increase was lower in the Stepping group than in the Wheelchair group. R^2 revealed that for both reaching modes, the linear increase of *CE* was more consistent in the Stepping group than in the Wheelchair group. Finally, the coefficient of variation (i.e., *SD/M*, indicating the overall variability of judgments) were lower than 15% in average and slightly lower in the rod conditions compared with the hand conditions (*CV* in Table 1).

DISCUSSION

We investigated the perception of whether an object is within reach by means of a locomotor task that did not provide feedback from physical contact. Participants viewed a stationary virtual target, moved around to explore the scene, and then stopped when they judged it to be within reach. The experimental setup created a situation in which the optic flow alone was ambiguous relative to the absolute egocentric distance of the object and in which the participants could not see their arm or the rod. Nevertheless, our results showed that participants regulated their locomotion on the basis of (a) the depicted target distance and (b) their reaching capabilities (e.g., arm length, tool).

Following Solomon and Turvey (1988), we expected that participants would be able to judge how far they could reach with a handheld rod. In both locomotion groups, the difference in judged distance between the hand and rod conditions accurately reflected the difference of actual maximum reachable distances. However, the difference between perceived distances in hand and rod reaching conditions disappeared when performance was scaled to the actual maximal reachable distance.

Some previous studies have selected participants, a priori, on the basis of their arm length (e.g., Carello et al., 1989). By contrast, our participants represented a continuous range of reaching capabilities. A posteriori, we split our sample into two clusters with longer and shorter actual maximum reaching distances. As expected, judged maximum reaching distance (expressed in centimeters) was greater in the Long cluster than in the Short cluster in both the hand and rod conditions. These differences between Short and Long clusters disappeared when judged distance was expressed as a percentage of actual reaching ability. These two findings indicate that participants accurately perceived environmental properties in relation to their own capabilities for action and validates our use of a locomotor response measure as an alternative to verbal or reaching response measures (Carello et al., 1989; Gabbard et al., 2007; Heft, 1993; Mantel et al., 2007; Mark et al., 1997; Rochat & Wraga, 1997).

Judgments were more accurate in the Wheelchair group than in the Stepping group as indicated by the *CE* comparison and by the lower slopes obtained for the linear regressions of *CE* as a function of target distance. This finding resembles Carello et al. (1989), who observed higher systematic errors when judgments were made standing (relative to judgments made while seated). Carello et al. related this effect to the challenge of maintaining upright stance (see also Rochat & Wraga, 1997). A related possibility is that the seat back on the wheelchair may have provided a physical referent that could aid in judgments of 1-*df* reaching ability (i.e., arm movements without leaning). At minimum, this result shows that reaching judgments were not more accurate in the context of a familiar mode of locomotion (stepping) than in the context of a novel mode of locomotion (wheelchair).

Judgment Accuracy

Participants tended toward slight underestimation ($M = 4.6$ cm) of the maximum distance from which they could reach objects. Although the magnitude of this error is within the range of that reported in studies using verbal (yes/no) response measures (e.g., Carello et al., 1989; Coello & Iwanow, 2006; Heft, 1993; Mark et al., 1997; Rochat & Wraga, 1997), its direction contrasts to the overestimations commonly observed in those studies. This difference may reflect the restriction, in our method, to judgments of 1-*df* reaching ability. When permitted to choose different reaching modes, participants typically switch from 1-*df* to multiple-*df* reaching. It is important to note that this switch does not occur at the maximum critical boundary for 1-*df* reaches (i.e., at the greatest possible distance that can be reached with the arm alone). Rather, the switch from 1-*df* to multiple-*df* reaching modes occurs earlier, at what Mark and colleagues (1997) called the preferred critical boundary. The difference in the direction of error (underestimation vs. overestimation) underscores the importance of the use of different response measures in assessing perception of action capabilities.

We found that the constant error of judgments increased as a function of the initial distance of targets. This finding indicates that responses were influenced by the range of distances tested. With existing data, it is difficult to evaluate whether the range influences verbal yes/no judgments in the same way as in that case only one estimate of perceived maximal reachable distance is derived using all target distances. The compression of perceptual space resembles what is often observed in studies of egocentric distance perception (e.g., verbal reports in centimeters or reaching) in which the slope of judged distance as a function of actual distance is lower than 1, a trend further increased when presentation of the object is monocular against a black background (Eriksson, 1974; Pagano & Bingham, 1998). A compression is also reported in studies investigating the perception of what can be reached with a rod both when the rod can be seen (e.g., Bongers, Michaels, et al., 2004) and when it can only be wielded (e.g., Solomon & Turvey, 1988). In agreement with these tendencies, we obtained a stronger compression in the rod reaching condition than in the hand condition.

Across participants, the coefficient of variation, which indicates the overall precision of judgments, ranged from 12.3% to 16.7%. These values were lower than the coefficient of variation values reported by Pagano and Bingham (1998) for verbal judgments without feedback (23 to 30%) and with feedback (19 to 21%). On the other hand, they obtained lower values for real reaches with feedback (6 to 11%; Pagano & Bingham, 1998). Thus, despite the compression of distance, locomotor judgments of reachability exhibit an overall accuracy similar to that usually observed with other tasks (e.g., actual reaches and verbal judgments in arm length units).

It is interesting to note that our locomotor response measure and the yes/no response measure are both means of assessing perceived reachability of objects. It has been argued that perception is influenced by the verbal/cognitive versus sensorimotor nature of the task (e.g., Bridgeman, Lewis, Heit, & Nagle, 1979; Goodale, Milner, Jakobson, & Carey, 1991; Schneider, 1969). However, the fact that judgments of action capabilities can both be obtained by our locomotor task or by verbal yes/no judgments (see also results from Coello et al., 2008; Coello & Iwanow, 2006) raises questions about how much reports of perceived distance depend upon the mode of response (e.g., verbal/cognitive vs. sensorimotor) as opposed to being influenced by the metrics in which judgments are expressed (e.g., centimeters, arm length units, reaching-ability).

Information About Absolute Distance

Participants judged how far they could reach. These judgments were expressed through locomotion; however, the judgments may also have been informed by locomotion. We monitored displacement of the head and used this information to update the display in real time. Thus, locomotion and other body movements (which displaced the head) generated optic flow. This fact raises questions about the information that was available to support perception. By itself, optic flow was ambiguous with respect to absolute distance. How might participants have scaled optic flow to yield information about absolute distance? One possibility is that information from other sensory systems (and/or hypothetical efferent copy of motor commands) is used to disambiguate optic flow (relative to absolute distance) via inferential processing. From an ecological point of view, it is not clear how direct perception and the principle of information pickup can be articulated with the postulate that available information about the object's distance from the perceiver is segmented and has to be reconstructed within the organism. Another possibility is that information specifying distance *across* multiple sensory systems is detected directly. Stoffregen and Bardy (2001) proposed that the relations between modal patterns of stimulation constitute information in their own right, information that is not available to individual perceptual systems. Formal analyses have shown that when a point of observation translates relative to a stationary object, the egocentric distance between them can be expressed as a function of the kinematics of the point of observation and the kinematics of the direction of the object relative to the direction of movement (Gibson, Olum, & Rosenblatt, 1955; Nakayama & Loomis, 1974). In our experiments, when the participants moved their head and torso relative to the illuminated (virtual) object, this affected not only the structure of light arriving to their eyes but also the stimulation of their vestibular system; the tension of their muscles, tendons, joints, and skin (e.g., in the neck and the back); the pressure of their body against the seat and/or of their feet against the floor; etc. Accordingly, the higher order relation between patterns of haptic/gravito-inertial stimulation (generated by displacement of the head relative to the gravito-inertial force environment) and optic flow (created by displacement of the head relative to the displayed object) could have been unambiguously related to absolute distance (Mantel et al., 2007).

CONCLUSION

We evaluated the perception of absolute distance in the context of judgments of whether (and when) a virtual object was within participants' reach. A novel feature of our study was that perceptual judgments were expressed through locomotion rather than through words or actual reaches as in previous studies. We found that judgments were substantially accurate when participants used a familiar form of locomotion (stepping) but also when they used a novel form of locomotion. Accuracy was substantially the same when participants judged when they were within arm's reach of the object and when they judged when they could reach the object using a handheld rod. Finally, participants with longer and shorter actual reaching capabilities gave judgments that were the same percentage of their actual reaching ability. These results validate our use of a locomotor response measure for judgments of absolute distance. Participants could not see their arms or the handheld rods. Several authors proposed that when an object is held or wielded, the patterns of haptic/gravito-inertial stimulation can provide information about the object's length (e.g., Solomon & Turvey, 1988). Whether similar patterns could provide information about the characteristics of an individual's own limbs is a question open for future research. Be that as it may, in judging when the object was within reach our participants were required to detect relations between information about the absolute distance of the virtual object (such as the intermodal structure we discussed) and nonvisual information about arm and/or rod length. How these relations were obtained remains to be seen.

ACKNOWLEDGMENTS

This research was supported by the "Enactive Interfaces" European Network of Excellence (IST 002114) and by the National Science Foundation (BCS-0236627).

The authors thank William Mace for his helpful comments on an earlier version of this article.

REFERENCES

Bingham, G. P., & Stassen, M. G. (1994). Monocular egocentric distance information generated by head movement. *Ecological Psychology, 6,* 219–238.

Bongers, R. M., Michaels, C. F., & Smitsman, A. D. (2004). Variations of tool and task characteristics reveal that tool-use postures are anticipated. *Journal of Motor Behavior, 36,* 305–315.

Bongers, R. M., Smitsman, A. W., & Michaels, C. F. (2004). Geometric, but not kinetic, properties of tools affect the affordances perceived by toddlers. *Ecological Psychology, 16,* 129–158.

Bridgeman, B., Lewis, S., Heit, G., & Nagle, M. (1979). Relation between cognitive and motor-oriented systems of visual position perception. *Journal of Experimental Psychology: Human Perception and Performance, 5,* 692–700.

Carello, C., Grosofsky, A., Reichel, F. D., Solomon, J., & Turvey, M. T. (1989). Visually perceiving what is reachable. *Ecological Psychology, 1,* 27–54.

Cliff, N. (1993). Dominance statistics: Ordinal analyses to answer ordinal questions. *Psychological Bulletin, 114,* 494–509.

Coello, Y., Bartolo, A., Amiri, B., Devanne, H., Houdayer, E., & Derambure, P. (2008). Perceiving what is reachable depends on motor representations: Evidence from a transcranial magnetic stimulation study. *PLoS ONE, 3,* e2862.

Coello, Y., & Iwanow, O. (2006). Effect of structuring the workspace on cognitive and sensorimotor distance estimation: No dissociation between perception and action. *Perception & Psychophysics, 68,* 278–289.

Eriksson, E. S. (1974). Movement parallax during locomotion. *Perception & Psychophysics, 16,* 197–200.

Gabbard, C., Cordova, A., & Lee, S. (2007). Examining the effects of postural constraints on estimating reach. *Journal of Motor Behavior, 39,* 242–246.

Gibson, J. J. (1986). *The ecological approach to visual perception.* Mahwah, NJ: Erlbaum. (Original work published 1979)

Gibson, J. J., Olum, P., & Rosenblatt, F. (1955). Parallax and perspective during aircraft landings. *American Journal of Psychology, 68,* 372–385.

Gogel, W. C., & Tietz, J. D. (1979). A comparison of oculomotor and motion parallax cues of egocentric distance. *Vision Research, 19,* 1161–1170.

Goodale, M. A., Milner, A. D., Jakobson, L. S., & Carey, D. P. (1991). A neurological dissociation between perceiving objects and grasping them. *Nature, 349,* 154–156.

Heft, H. (1993). A methodological note on overestimates of reaching distance: Distinguishing between perceptual and analytic judgments. *Ecological Psychology, 5,* 255–271.

Lee, D. N. (1980). The optic flow field: The foundation of vision. *Philosophical Transactions of the Royal Society of London, B, 290,* 169–179.

Longuet-Higgins, H. C. (1986). Visual motion ambiguity. *Vision Research, 26,* 181–183.

Mantel, B., Bardy, B. G., & Stoffregen, T. A. (2007). Perceiving what is within reach from intermodal patterns. In A. Luciani & C. Cadoz (Eds.), *Proceedings of the 4th International Conference on Enactive Interfaces* (pp. 169–172). Grenoble, France: ACROE.

Marcilly, R., & Luyat, R. (2008). The role of eye height in judgment of an affordance of passage under a barrier. *Current Psychology Letters, 24,* 12–24.

Mark, L. S. (1987). Eye-height-scaled information about affordances: A study of sitting and stair climbing. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 361–370.

Mark, L. S., Nemeth, K. , Gardner, D. , Dainoff, M. J., Paasche, J., Duffy, M., & Grandt, K. (1997). Postural dynamics and the preferred critical boundary for visually guided reaching. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 1365–1379.

Nakayama, K., & Loomis, J. M. (1974). Optical velocity patterns, velocity-sensitive neurons, and space perception: A hypothesis. *Perception, 3,* 63–80.

Ooi, T. L., Wu, B., & He, Z. J. (2006). Perceptual space in the dark affected by the intrinsic bias of the visual system. *Perception, 35,* 605–624.

Pagano, C. C., & Bingham, G. P. (1998). Comparing measures of monocular distance perception: Verbal and reaching errors are not correlated. *Journal of Experimental Psychology: Human Perception and Performance, 24,* 1037–1051.

Pagano, C. C., Grutzmacher, R. P., & Jenkins, J. C. (2001) Comparing verbal and reaching responses to visually perceived egocentric distances. *Ecological Psychology, 13,* 197–226.

Panerai, F., Cornilleau-Pérès, V., & Droulez, J. (2002). Contribution of extraretinal signals to the scaling of object distance during self-motion. *Perception & Psychophysics, 64,* 717–731.

Peh, C. H., Panerai, F., Droulez, J., Cornilleau-Pérès, V., & Cheong, L. F. (2002). Absolute distance perception during in-depth head movement: Calibrating optic flow with extra-retinal information. *Vision Research, 42,* 1991–2003.

Rochat, P., & Wraga, M. (1997). An account of the systematic error in judging what is reachable. *Journal of Experimental Psychology: Human Perception and Performance, 23,* 199–212.

Rosenblum, L. D., Wuestefeld, A. P., & Anderson, K. L. (1996). Auditory reachability: An affordance approach to the perception of sound source distance. *Ecological Psychology, 8,* 1–24.

Schneider, G. E. (1969). Two visual systems. *Science, 163,* 895–902.

Sedgwick, H. A. (1986). Space perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. 1. Sensory processes and perception* (pp. 21.1–21.57). New York, NY: Wiley.

Solomon, H. Y., & Turvey, M. T. (1988). Haptically perceiving the distances reachable with hand-held objects. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 404–427.

Stappers, P. J. (1992). *Scaling the visual consequences of active head movements: A study of active perceivers and spatial technology* (Doctoral thesis, Delft University, The Netherlands.

Stoffregen, T. A. (2003). Affordances as properties of the animal-environment system. *Ecological Psychology, 15,* 115–134.

Stoffregen, T. A., & Bardy, B. G. (2001). On specification and the senses. *Behavioral and Brain Sciences, 24,* 213–261.

Thomson, J. A. (1983). Is continuous visual monitoring necessary in visually guided locomotion? *Journal of Experimental Psychology: Human Perception and Performance, 9,* 427–443.

Warren, W. H., Jr., & Whang, S. (1987). Visual guidance of walking through apertures: Body-scaled information for affordances. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 371–383.