Perception, 2003, volume 32, pages 567 – 578

DOI:10.1068/p5041

A comparison of visual and nonvisual sensory inputs to walked distance in a blind-walking task

Colin G Ellard, Sarah C Shaughnessy
Department of Psychology, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada;
e-mail: cellard@watarts.uwaterloo.ca
Received 24 July 2002, in revised form 16 October 2002; published online 4 April 2003

Abstract. Two experiments were conducted in order to assess the contribution of locomotor information to estimates of egocentric distance in a walking task. In the first experiment, participants were either shown, or led blind to, a target located at a distance ranging from 4 to 10 m and were then asked to indicate the distance to the target by walking to the location previously occupied by the target. Participants in both the visual and locomotor conditions were very accurate in this task and there was no significant difference between conditions. In the second experiment, a cue-conflict paradigm was used in which, without the knowledge of the participants, the visual and locomotor targets (the targets they were asked to walk to) were at two different distances. Most participants did not notice the conflict, but despite this their responses showed evidence that they had averaged the visual and locomotor inputs to arrive at a walked estimate of distance. Together, these experiments demonstrate that, although they showed poor awareness of their position in space without vision, in some conditions participants were able to use such nonvisual information to arrive at distance estimates as accurate as those given by vision.

1 Introduction

In a much-cited experiment, Thomson (1983) showed that it was possible to walk to a target after a short visual presentation and without subsequent visual input. Thomson's original study and a host of replications and extensions that followed (Bigel and Ellard 2000; Elliott 1986; Glasauer et al 1994; Loomis et al 1992; Rieser et al 1990; Steenhuis and Goodale 1988) have shown that we are able to complete such blind-walking tasks with high precision over a range of distances up to about 25 m, though there is some tendency for accuracy to decrease with increasing stimulus distance. This finding suggests that we must possess some sort of calibration between the location of a target on the ground plane and the movements (and the sensory consequences of those movements) that are required to walk to the target. It is very likely that this calibration is more complex and interesting than a simple sensorimotor association between target appearance and movement. Numerous spatial updating studies have demonstrated that participants retain an accurate record of target location as they walk. For example, in his original experiments, Thomson (1983) demonstrated that, if participants were halted unexpectedly during the execution of a trial and asked to throw an object at the target, they could do so. More recently, Fukusima et al (1997) have shown that participants can triangulate to a previously viewed target after walking on an indirect route away from it. The existence of such an accurate representation of target location is all the more interesting considering that a number of studies have demonstrated that, when asked to make perceptual judgments of the distances between objects on the ground, we are not always as accurate. Such distance estimates suffer foreshortening errors, presumably because equal intervals on the ground plane are subtended by diminishing visual angles as target distance increases (Gilinsky 1951; Loomis et al 1992). The discrepancy between the ability to estimate distance as assessed in walking tasks and in tasks requiring other kinds of responses (such as verbal responses) has been the focus of some recent attention, and may have important implications for the way in which we represent space. One possibility is that such dissociations between the way that space is used and the way it is described may relate to the existence of separate neural systems that are dedicated to different kinds of visual analyses for specific purposes (Milner and Goodale 1995). A number of other possible explanations have also been described. For example, recent evidence suggests that Gilinsky (1951) may have overestimated the extent of the nonlinearity in egocentric distance perception. Foley et al (2001) have demonstrated that the extent of a perceived depth interval can be influenced by its angular size. Loomis et al (2002) have demonstrated that it is possible to dissociate the perception of the shape of objects lying on a ground plane and the perception of the egocentric distances to those objects, even under conditions where the required response (a verbal estimate) is the same in both cases. They showed that perception of shape is more prone to perspective foreshortening under monocular viewing conditions than under a binocular viewing condition. Perception of egocentric distance is not affected by such differences in viewing conditions.

Although much data suggest that brief visual presentations can generate representations of target location that support precise performance in walking tasks, there has been less attention paid to the question whether other kinds of sensory information can be used to support such precise performance. The blind-walking task depends on our ability to determine our relationship to the target location by means of sensory and motor feedback information derived from senses other than vision. One might therefore predict that such information, when used as the input in a blind-walking task, would be able to support performance as accurate as that seen in the versions of the task first used by Thomson. This question was examined directly in three studies (Bigel and Ellard 2000; Klatzky et al 1990; Loomis et al 1993), and findings from all three studies were roughly comparable in showing that participants trying to reproduce walked distances ranging from 4 to 8 m tended to underestimate distance by about 5%–10%. The two earlier studies showed overestimates of reproduced distance for very short distances (2 m). Only the study by Bigel and Ellard (2000) included a direct comparison of errors on the blind-walking task where either visual or locomotor targets were used as inputs or where participants were provided with both visual and locomotor targets. In this experiment, some participants were simply shown a target and asked to walk to it. Others were led blindly to the target and then returned to the starting point. A third group of participants both saw the target and were led to it. The main findings suggested that individuals were significantly more accurate at estimating distances to visual targets than to locomotor targets and that, although providing both kinds of inputs did not improve accuracy per se, it did result in a curious and unexplained tendency to overestimate target distance. The difference in accuracy between estimates to visual and locomotor targets is paradoxical. Our ability to walk accurately to visual targets is presumably predicated on an ability to monitor precisely whatever nonvisual information is being used to guide us to the previously seen target. Yet when such information is used as the input for the task, our performance is markedly poorer. One possible explanation for the discrepancy is that memory for locomotor distance is more vulnerable to decay than visual memories of distance. Although it is very difficult to disentangle all of the sources of sensory information that are at play during walking without vision, some progress has been made in analysing sensory contributions to path integration in other kinds of tasks that may have some relevance to performance during walking. A number of separate sources of information are available to update location during movement. Both vestibular and proprioceptive information can be used and these combine linearly (Hlavacka et al 1992; Israël and Berthoz 1989). In addition, it is possible that efference copy plays a role in such distance computations (von Holst and Mittelstaedt 1950; Mittelstaedt and Mittelstaedt 2001). However, the fact that individuals who are transported passively in robotic vehicles display reasonable distance estimation suggests that efference copy is not necessary for distance computation in walking tasks (Israël et al 1997).

The purpose of the present experiments was twofold. First, we wanted to compare directly the performance of individuals on the conventional blind-walking task when target information was provided either visually or by walking, but in a task free of some complicating factors that conspire against accurate performance. The main experimental question was whether, under any conditions, reproductions of walked distance could be as accurate as walked estimates of seen distances. Second, we wanted to assess the relative contributions of visual and walked distances using a cue-conflict paradigm, in which subjects were presented with offsets between visual and locomotor targets, but were told that the two were congruent. This approach allowed us to compare quantitatively the weighting of perceived visual and locomotor target location to performance in the blind-walking task.

2 Experiment 1

In this experiment, participants were presented either with a visual target or a locomotor target and, in the test phase, they were asked to reproduce target distance by walking. Unlike previous such studies, we took several measures to make the task easier. First, rather than being led, participants were allowed active control of walking during the input phase of the task. Some evidence (Philbeck et al 2001) suggests that such active control facilitates nonvisual navigational performance. Second, by using guide ropes, we eliminated the potentially confusing contribution of unintended changes of heading (Boyadjian et al 1999). Third, we conducted the experiment in an outdoor setting, where more accurate blind-walking performance is often seen, perhaps because of decreased concerns by participants that they might collide with obstacles or walls in the testing space (Bigel and Ellard 2000; J W Philbeck, personal communication).

2.1 *Participants*

All participants were undergraduate students at the University of Waterloo who received course credit for their involvement in the experiment. Their participation in the experiment was approved by the Office of Human Research at the University of Waterloo. The only criterion for participation was that the participants had normal vision with or without correction and were able to walk a distance of 12 m. All participants were naïve to the purpose of this experiment. Fifteen men and fifteen women participated in this experiment.

2.2 *Experimental setting*

A plot of flat, grassy land on the University of Waterloo campus was used for the testing area. The participants began with their feet behind a wooden dowel. On either side of the dowel was an aluminium stake to which a yellow rope was attached. The same ropes were attached to another pair of stakes at a distance of 12 m. A set of supporting ropes ensured that there was virtually no sag in the ropes that could serve as a haptic cue. Over the course of the 12 m walkway, the height of the rope above the ground varied by less than 1 cm. The visual target consisted of a red flag attached to a wooden stake. The rope and the top of the flag were set at a height of 1 m. The two ropes were set 1 m apart.

2.3 *Procedure*

2.3.1 *Practice session.* All participants underwent a practice session before testing so they would become more accustomed to navigating without vision. The practice session consisted of eight trials. Participants stood at the starting location with their feet behind a wooden dowel and they were instructed to hold on to both of the ropes. Participants in the vision group viewed the target for 10 s. Following this, they were asked to wear the opaque goggles and to walk forwards while using the ropes to prevent turning and to stop when they felt they had reached the location of the target. Participants in the locomotor group were asked to wear opaque goggles and walked forward while holding on to the ropes. Once they reached the target location, they were asked to stop, turn around, and return to the starting location, all the while wearing the opaque goggles. Immediately afterwards, they were asked to walk back to the target location without removing their goggles. In both conditions, when the participants stopped walking, the experimenter provided feedback on their distance from the target location. On practice trials the target was set at distances of 2, 4, 6, 8, or 10 m from the start position. To prevent participants from simply counting their steps, they were asked to repeat nonsense rhymes out loud. Different rhymes were used on the outbound and inbound portions of the walk. In pilot sessions, the experimenters observed that these procedures made it extremely difficult to make accurate counts of steps. Participants were instructed to hold the ropes gently in order to prevent veering, but were instructed not to pull on the ropes with any force.

2.3.2 *Test session.* On test trials, participants completed one trial at each of 4, 6, 8, and 10 m. Responses were measured with a measuring tape running parallel to the rope on the left side. Although participants in the vision condition could see the tape, it was kept face down during target viewings to prevent it from providing any unintended information about target distance.

2.4 *Results*

The main result of the experiment is shown in figure 1. As can be seen, participants were able to complete the blind-walking task to either visual or locomotor targets with high accuracy. Analysis of signed error scores was used to assess whether or not there were systematic tendencies to undershoot or overshoot the targets in any conditions. There was no evidence of any group effects (vision versus locomotor: $F_{1,26} = 0.309$, $p > 0.1$) other than the presence of an interaction between gender, input condition, and target distance ($F_{3,78} = 2.741$, $p < 0.05$). Decomposition of the interaction showed that women had a tendency to overestimate the distance of the 10 m targets in the locomotor condition compared to the visual condition (target distance × input type: $F_{3,39} = 3.075$, $p < 0.05$).

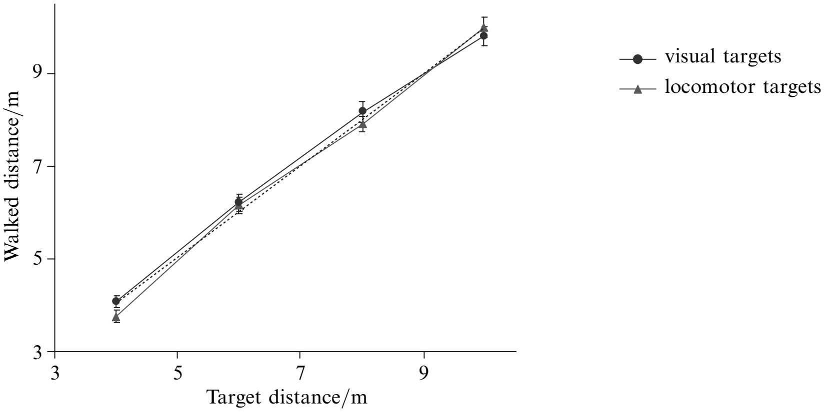

Figure 1. A line graph showing the performance of participants in experiment 1. Each data point represents the averaged performance of all participants in a given condition and error bars represent standard error of the mean. Results for the visual and locomotor conditions are plotted separately. The dotted line represents perfect performance.

2.5 *Discussion*

The main finding in this experiment was that participants were just as precise when walking to locomotor targets as they were when walking to targets that they had seen. This finding stands in contrast to previous experiments in which participants have been asked to walk to targets that they have never seen. In those previous studies, at least a small difference between locomotor and visual target precision was seen, and in some cases (Bigel and Ellard 2000) the difference was quite marked. There are several differences between the procedure used in the present experiment and those used in previous studies. For one thing, the roped walkway made it easier for participants to walk under active control without veering. In previous experiments, assisted walking procedures of one kind or another were always used. Independent evidence (Philbeck et al 2001) suggests that such procedures are likely to produce somewhat inflated errors. We do not think that participants were able to compute location using haptic information from the ropes. For one thing, we ensured that there was little sag in the ropes. Other than sag, the only other detectable quantity that might allow computation of location would be differences in tautness that might be detected at different locations. Even if participants disobeyed our instruction to avoid pulling on the ropes (and there was no evidence that they did so), one would expect the quality of such information to vary systematically with the distance from the stakes, and so we would expect to see a monotonic relationship between precision and distance. Other than a slight increase in variability at the longest distance (which is the opposite of what the use of haptic information would predict), no such relationship was observed.

Another difference between our experiment and some previous studies is that in our locomotor condition participants were asked to return to the starting position before beginning the test phase of the experiment. In some other studies (Klatzky et al 1990, 1995), participants were asked to first walk an interval, and then during the test phase to walk a matching interval in the same direction as the first one. Although the two procedures have never been compared directly, it is possible that the matching procedure is more difficult. If the information that is used for path integration exists in a form that allows one to continuously update one's position with respect to an origin, then returning to a starting position would use that information quite directly. Using such information to produce a matched distance might be an entirely different process that would require an additional and possibly effortful data transformation. Even if there are no other differences, the fact that our participants were asked to walk out to the target and then to return to the starting position before the test phase of the trial meant that they effectively had two presentations of the stimulus distance before beginning the test trial. In future experiments, we intend to explore the differences between tasks that require interval matching by walking and those that require homing.

Although this experiment is not sufficient by itself to distinguish between these possibilities, it establishes that under the right conditions it is possible to estimate distances to locomotor targets with precision equal to that seen for visual targets. The error values recorded in this study were considerably smaller than those seen in previous similar studies (Bigel and Ellard 2000; Klatzky et al 1990; Loomis et al 1993; Rieser et al 1990; Thomson 1983). This supports the notion that, in an easier task, performance in a locomotor condition can equal that seen for visual targets.

It should be noted that the mechanics of the task we used required that during both practice and test sessions the participants received more exposures to the locomotor target than to the visual target. By virtue of our requirement that participants return to the origin at the end of each trial, participants in the locomotor group received twice as many exposures to the target distance as those in the visual group. Although this difference may have accounted for some of the improvement in the locomotor group compared to previous similar studies, we note that a similar procedure was employed in our earlier work (Bigel and Ellard 2000), in which performance with locomotor targets was significantly poorer than with visual targets.

We also note that the distances that were employed during the practice session were similar to those used in testing, other than the inclusion of a 2 m distance in practice sessions. It is likely that exposure to these target distances prior to testing produced a training effect and would have contributed to the level of performance in the experiment. However, as similar practice regimens in other experiments have not supported such precise performance (Bigel and Ellard 2000), we do not think this procedural detail accounts completely for our failure to find a measurable difference between the visual and locomotor conditions. In future experiments, we intend to test this possibility directly.

Finally, the small gender effect needs to be addressed. Some evidence suggests that men may be more sensitive to internal sources of information in navigation tasks (Antes et al 1988; Bever 1992; Williams and Meck 1991), but the gender effect reported here does not seem to conform to that general pattern in any way that is easy to discern. Pending further experimental work, we are unable to offer any ready explanation for the small gender effect that we observed. Others have suggested that the well-documented gender differences in certain types of spatial cognitive tasks, such as mental rotation, are related to evolved differences in navigational abilities (Dabbs et al 1998; Moffat et al 1998; Silverman et al 2000), but the reported correlations between these two very different types of tasks are quite weak and somewhat inconsistent.

3 Experiment 2

In the first experiment we showed that, when task demands were low, participants were able to show levels of accuracy in estimating distance to a locomotor target that approached those found for visual targets. This finding suggests that it is plausible to imagine that locomotor target information may be sufficiently precise for it to contribute to estimates of distance in tasks where multiple sources of information regarding distance are available. The goal in the second experiment was to assess the size of these contributions in a quantitative manner by presenting participants with misleading information about the relationship between visual and locomotor targets. A paradigm resembling that used in cue-conflict studies (Pick et al 1969; Warren and Pick 1970; Welch and Warren 1986, for example) was employed in which participants were presented with a visual target and were also walked to a locomotor target. In some conditions, and without the knowledge of participants, the visual and locomotor targets were at different distances from the participant. If locomotor target information contributes to distance estimation, then such cue conflicts should affect performance on test trials, and the size of the effect could be used to estimate the relative size of the contribution of locomotor target information. According to Ernst and Banks (2002), statistically optimal cue combination using maximum likelihood estimation (MLE) would require the weightings given to contributions from each cue to be proportional to their individual variance. Ernst and Banks have demonstrated robust use of the MLE rule in a visual – haptic conflict task. Experiment 1 showed that in our blind-walking task, there was no difference in accuracy between participants who were provided with visual information and those who received only locomotor information about the position of the target. In this case, MLE estimation would predict that, all other factors being equal, the weightings of visual and locomotor inputs should be approximately equal, with values of about 0.5.

3.1 *Participants*

Fifteen men and fifteen women participated voluntarily in this experiment, and received course credit for their involvement. All participants were undergraduate students at the University of Waterloo. The only criterion for participation was that the participants had normal vision with or without correction and were physically able to walk a distance of 12 m. All participants were naïve to the purpose of this experiment.

3.2 *Experimental setting*

The setup was the same as in experiment 1.

3.3 *Procedure*

Following a brief practice session, subjects were tested by a procedure similar to that described in experiment 1. The practice session consisted of eight trials with target distances ranging from 4 to 10 m in 2 m increments. On each trial, participants were first shown the target and then walked to it wearing the opaque goggles. They were then returned to the starting position, turned around to face the target, and then asked to walk to the target without vision. For the test session, there were eight trials, and each one provided participants with both locomotor cues and visual cues. Participants were told that they would view a target and then they would be walked to the target and back to the starting point in order to help them to learn the location of the target. On each of the trials, the visual target was presented at 4, 6, 8, or 10 m as in experiment 1; but on two of the trials we introduced conflicting sensory cues: on one trial, the visual target was presented at 8 m and the locomotor target was presented at 6 m (V8L6 or L6V8, depending on the order of presentation); on the other conflict trial, the visual target was presented at 6 m and the locomotor target was at 8 m (V6L8 or L8V6, depending on the order of presentation). In this way, it was possible to compare performance with trials at 6 and 8 m in which the visual and locomotor targets were congruent. All participants performed all eight trials and the order of presentation was randomised. In addition, because visual and locomotor targets needed to be presented one after another, target order was counterbalanced by presenting half of the participants with the locomotor target first and the other half of participants with the visual target first. Each participant received only one of the two possible target orders.

3.4 *Results*

Very few participants noticed the discrepancies that were introduced between the visual and locomotor targets during testing. Three participants, at the conclusion of testing, reported spontaneously that they had felt as though on some trials the visual and locomotor targets did not correspond. Five other participants, when prompted during debriefing, reported having experienced some vague sensation that there was something unusual about the test trials. The other twenty-two participants did not report having noticed anything unusual during the experiment, even when prompted specifically during debriefing. When informed of the manipulation, most participants expressed considerable surprise.

Signed error values can give information about the relationship between the average response value and the location of the target (ie whether the participants were overshooting or undershooting the targets). An ANOVA was conducted on the signed error values for the two conflict trials and, for comparison, the two congruent trials with targets set at 6 and 8 m. Preliminary analysis showed no significant gender effect ($F_{1,26} = 2.39$, $p > 0.1$) nor any significant interactions involving gender, so data were combined for subsequent analyses. There was a significant interaction between target order and trial type ($F_{3,84} = 6.92$, $p < 0.01$), and so the effects for the vision last and locomotion last trials were analysed separately and are plotted separately in figure 2.

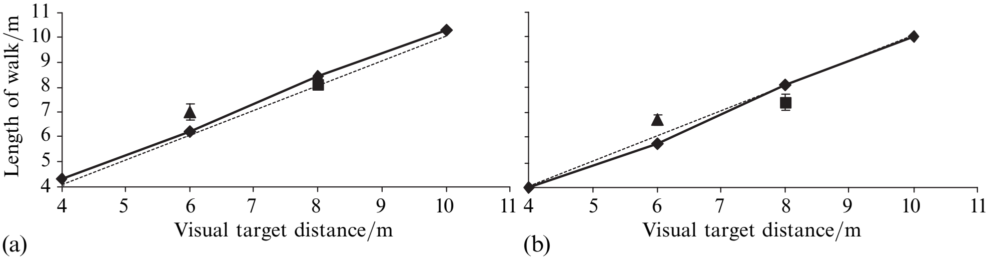

Figure 2. Line graphs showing the performance of participants in experiment 2 in which the visual target was presented last (a) and the locomotor target was presented last (b). The congruent trials (connected by the line) are shown separately from the conflict trials. Conflict-trial performance is shown relative to the last presented target [visual for (a) and locomotor for (b)].

With both target orders, the conflict trials affected results in the predicted directions, but there was a strong effect of target order. When the visual target was presented last, participants undershot the seen position of the target slightly in the L6V8 but showed a large overshoot of the visual target in the L8V6 condition. When the locomotor targets were presented last, there was both a significant undershoot in the V8L6 condition and a significant overshoot in the V6L8 condition.

In order to test the prediction that visual and locomotor presentations of target distance contributed about equally to estimates of distance, we converted each participant's score to a weighting value ranging from 0 to 1, where the value was derived by computing the relative distance of the participant's distance estimate from the visual and proprioceptive targets as a ratio. In other words, if the visual target was at 6 m and the proprioceptive target was at 8 m, a response of 6 m would obtain a weighting value of 0 for proprioception and a response of 7 m would be given a value of 0.5. These values are shown in figure 3. The weighting values were entered into an ANOVA with order and gender as factors. The analysis showed a significant effect of order ($F_{1,26} = 13.71$, $p < 0.001$). There was no effect of gender nor any significant interaction.

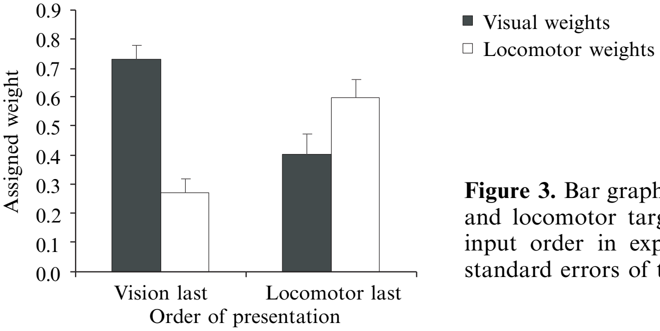

Figure 3. Bar graphs showing the weighting of visual and locomotor target information as a function of input order in experiment 2. Error bars represent standard errors of the mean.

Because the results of the first experiment suggested that there was no significant difference in peoples' ability to walk intervals experienced visually or through proprioception, one would predict that each of these two sources of information ought to be weighted equally to be used optimally. In order to test this prediction, we compared the obtained weighting values with a theoretical value of 0.5. Because of the interaction with order of presentation, we conducted this test separately for the vision first and walk first conditions. Results of these tests showed that, when the visual presentation was first, the weighting of visual information did not differ significantly from the predicted value of 0.5 ($t_{14} = -1.369$, $p > 0.1$). When the visual presentation was last, the weighting of visual information was significantly greater than 0.5 ($t_{14} = 4.68$, $p < 0.001$).

3.5 *Discussion*

The main finding in this experiment was that when people were presented with conflicting visual and locomotor targets in a blind-walking task, they used both sources of information together to arrive at one blended estimate of target location. This finding represents the first direct demonstration that locomotor information contributes to distance estimation even when visual information has been made available.

This finding extends the results reported by Bigel and Ellard (2000), in which we were able to show that, although providing locomotor information in a blind-walking task did not increase accuracy, it did exert a subtle influence on performance, in that case by producing a slight tendency to overshoot target locations. In the present experiment, the evidence is much more straightforward in its suggestion that locomotor information contributes directly to distance estimation.

Although both visual and locomotor information contributed to the final estimate of target distance in this task, there was a marked effect of the order of presentation of the two inputs. When the visual input was given last, its weighting was significantly greater than predicted by the MLE rule, given the outcome of experiment 1. When the locomotor input was last, the weightings of the visual and locomotor inputs were equal and in accord with the prediction of statistical optimality theory. Other researchers have suggested that the relative weighting of vision and other perceptual cues may be adjusted depending upon their sensitivity in prevailing conditions. For example, van Beers et al (2002) have shown in a task requiring estimation of hand position in space, that visual – proprioceptive integration varies with the direction of the hand in space. In some circumstances, the visual input dominates estimates of hand position, but in others this state of affairs is reversed such that the proprioceptive input dominates. This effect is predicted by the way in which the precision of the visual input varies with visual direction. If the same kind of explanation is true of the shift in relative weightings of visual and locomotor information in our task, then it must mean that the relative precision of the two inputs changes depending on the order in which they are presented. It is not likely that this change in precision is a perceptual effect, especially given the findings in experiment 1. One possibility is that locomotor target information may decay more rapidly than visual target information, suggesting that our finding is more of a memory effect than a perceptual effect. Another possibility is that visual target information actually interferes with locomotor target information, so that when the visual information is presented last it masks the preceding locomotor target information. Both of these possibilities suggest that, in addition to the simple precision of perceptual inputs, additional cognitive variables may influence the outcome of sensory-integration experiments.

An important caveat to the application of optimality theory to the present experiment is the possibility that some of the differences in estimates of target distance in both experiments may be hidden by the variance in the ability to reproduce an estimated distance. If this latter variance were to be much larger than perceptual variance, it is possible that some differences in perceptual variance would be masked. Nevertheless, it is difficult to imagine that such masking effects could erase the large effect of order of presentation that we report.

One of the most remarkable aspects of this experiment was that participants were, for the most part, unaware of the manipulation despite the fact that the visual and locomotor target positions differed on some trials by more than 30%. Given the overall accuracy with which participants were able to localise targets on congruent trials, the fact that incongruencies were not noticed makes it quite unlikely that some kind of cognitive correction was taking place and could account for the averaging that we saw.

Combined with the findings from experiment 1, which showed that participants can learn to walk to locomotor targets with as much accuracy as they can walk to visual targets, this finding suggests a fascinating dissociation between what is known and what can be done that is reminiscent of that seen in blindsight patients (Weiskrantz 1980). This conclusion is bolstered by previous research in our laboratory showing that, when people are asked to make verbal estimates of targets they have walked to but never seen, their estimates are very inaccurate (Bigel and Ellard 2000). Our claim is also very much in accord with anecdotal evidence from other laboratories (Andre and Rogers 2002) showing that, despite good performance on blind-walking tasks, participants are very skeptical about their ability to carry out such tasks with any precision.

In contrast with most blind-walking studies, but in accord with our earlier finding, there was a slight tendency for participants to overshoot target locations on congruent trials. We have no ready way to account for this finding other than to suggest that at least some of the undershooting that is normally seen in blind-walking experiments may be a consequence of the natural fear of participants that they will collide with obstacles, along with their apparently very poor ability to know how far they have walked. It is possible that these factors conspire to produce very conservative behaviour, and that in our experiment where participants receive extensive practice at walking to targets they cannot see that this conservative behaviour is lessened. A similar suggestion was made originally by Werner and Wapner (1955) when they posited a 'psychological distance' value that depended on the perceived risk associated with the geometry of a testing space and, more recently, some similar effects have been observed in a triangle completion task by Nico et al (2002).

Overall, there was a slight tendency for the locomotor target to exert a stronger effect on behaviour on those trials in which the visual target was closer than the locomotor target than on those trials on which the visual target was further away. Without further experiments, any conclusions about this asymmetry must be premature, but one possibility is that this finding is related to the general tendency to undershoot on blind-walking tests. Given this, it may be that, when participants were led *past* the location of the target they had seen, this represented a phenomenally larger discrepancy between visual and locomotor target position than when they were led to a position short of the visual target location. In a preliminary report, Hall and Philbeck (2001) described some related spatial asymmetries concerned with locations in space that were either in front of or behind the viewer.

In conclusion, the main findings in our paper are, first, that when they can walk under active control and without having to reproduce heading, people are able to reproduce a walked distance that they have not seen with accuracy that is comparable to their accuracy when walking to a previously viewed target; and, second, that when there is a conflict between the visual and locomotor target distance, both inputs contribute about equally to target localisation in a walking task. Finally, our experiments suggest that this precise use of locomotor target information is carried out largely without awareness, as even very large discrepancies between visual and locomotor target locations are generally not noticed.

Acknowledgments. This research was funded by a grant from the Natural Sciences and Engineering Research Council of Canada. The authors wish to thank Jack Loomis and two anonymous referees for their comments on these experiments.

References

Andre J, Rogers S, 2002 "Perceivers walk the walk but talk short: Evidence for two visual pathways in distance perception" *Journal of Vision* **2**(7) 60a (abstract)

Antes J R, McBride R B, Collins J D, 1988 "The effect of a new city traffic route on the cognitive maps of its residents" *Environment and Behavior* **20** 77 – 91

Beers R J van, Wolpert D M, Haggard P, 2002 "When feeling is more important than seeing in sensorimotor adaptation" *Current Biology* **12** 834 – 837

Bever T, 1992 "The logical and extrinsic sources of modularity", in *Modularity and Constraints in Language and Cognition* volume 25 of the Minnesota Symposia on Child Psychology, Eds M Gunar, M Maratsos (Hillsdale, NJ: Lawrence Erlbaum Associates) pp 179 – 212

Bigel M G, Ellard C G, 2000 "The contribution of nonvisual information to simple place navigation and distance estimation: An examination of path integration" *Canadian Journal of Experimental Psychology* **54** 172 – 184

Boyadjian A, Marin L, Danion F, 1999 "Veering in human locomotion: The role of effectors" *Neuroscience Letters* **265**(1) 21 – 24

Dabbs J M, Chang E-L, Strong R A, Milun R, 1998 "Spatial ability, navigation strategy, and geographic knowledge among men and women" *Evolution and Human Behavior* **19** 89 – 98

Elliott D, 1986 "Continuous visual information may be important after all: A failure to replicate Thomson (1983)" *Journal of Experimental Psychology: Human Perception and Performance* **12** 388 – 391

Ernst M O, Banks M S, 2002 "Humans integrate visual and haptic information in a statistically optimal fashion" *Nature* **415** 429 – 433

Foley J M, Ribeiro-Filho J P, Da Silva J A, 2001 "Visual localization and the metric of visual space in multi-cue conditions" *Investigative Ophthalmology & Visual Science* **42** S939

Fukusima S S, Loomis J M, Da Silva J A, 1997 "Visual perception of egocentric distance as assessed by triangulation" *Journal of Experimental Psychology: Human Perception and Performance* **23** 86 – 100

Gilinsky R, 1951 "Perceived size and distance in visual space" *Psychological Review* **58** 460 – 482

Glasauer S, Amorim M A, Vitte E, Berthoz A, 1994 "Goal-directed linear locomotion in normal and labyrinthine-defective subjects" *Experimental Brain Research* **98** 323 – 335

Hall J, Philbeck J, 2001 "Do we update locations more poorly as they pass behind us?" *Journal of Vision* **1**(3) 138a (abstract)

Hlavacka F, Mergner T, Schweigart G, 1992 "Interaction of vestibular and proprioceptive inputs for human self-motion perception" *Neuroscience Letters* **138** 161 – 164

Holst E von, Mittelstaedt H, 1950 "Das Reafferenzprinzip. Wechselwirkungen zwischen Zentralnervensystem und Peripherie" *Naturwissenschaften* **37** 464 – 476

Israël I, Berthoz A, 1989 "Contribution of the otoliths to the calculation of linear displacement" *Journal of Neurophysiology* **62** 247 – 263

Israël I, Grasso R, Georges-François P, Tsuzuku T, Berthoz A, 1997 "Spatial memory and path integration studied by self-driven passive linear displacement. I. Basic properties" *Journal of Neurophysiology* **77** 3180 – 3192

Klatzky R L, Golledge R G, Loomis J M, Cicinelli J G, Pellegrino J W, 1995 "Performance of blind and sighted persons on spatial tasks" *Journal of Visual Impairment and Blindness* **89** 70 – 82

Klatzky R L, Loomis J M, Golledge R G, Cicinelli J G, Doherty S, Pellegrino J W, 1990 "Acquisition of route and survey knowledge in the absence of vision" *Journal of Motor Behaviour* **22** 19 – 43

Loomis J M, Da Silva J A, Fujita N, Fukusima S S, 1992 "Visual space perception and visually directed action" *Journal of Experimental Psychology: Human Perception and Performance* **18** 906 – 921

Loomis J M, Klatzky R L, Golledge R G, Cicinelli J G, Pellegrino J W, Fry P A, 1993 "Nonvisual navigation by the blind and sighted: Assessment of path integration ability" *Journal of Experimental Psychology: General* **122** 73 – 91

Loomis J M, Philbeck J W, Zahorik P, 2002 "Dissociation between location and shape in visual space" *Journal of Experimental Psychology: Human Perception and Performance* **28** 1202 – 1212

Milner A D, Goodale M A, 1995 *The Visual Brain in Action* (Oxford: Oxford University Press)

Mittelstaedt M-L, Mittelstaedt H, 2001 "Idiothetic navigation in humans: Estimation of path length" *Experimental Brain Research* **139** 318 – 322

Moffat S D, Hampson E, Hatzipantelis M, 1998 "Navigation in a 'virtual' maze: Sex differences and correlation with psychometric measures of spatial ability in humans" *Evolution and Human Behavior* **19** 73 – 87

Nico D, Israël I, Berthoz A, 2002 "Interaction of visual and idiothetic information in a path completion task" *Experimental Brain Research* **146** 379 – 382

Philbeck J W, Klatzky R L, Behrmann M, Loomis J M, Goodridge J, 2001 "Active control of locomotion facilitates nonvisual navigation" *Journal of Experimental Psychology: Human Perception and Performance* **27** 141 – 153

Pick H L, Warren D H, Hay J C, 1969 "Sensory conflict in judgments of spatial direction" *Perception & Psychophysics* **6** 203 – 205

Rieser J J, Ashmead D H, Talor C R, Youngquist G A, 1990 "Visual perception and the guidance of locomotion without vision to previously seen targets" *Perception* **19** 675 – 689

Silverman I, Choi J, Mackewn A, Fisher M, Moro J, Olshansky E, 2000 "Evolved mechanisms underlying wayfinding: Further studies on the hunter-gatherer theory of spatial sex differences" *Evolution and Human Behavior* **21** 201 – 213

Steenhuis R E, Goodale M A, 1988 "The effects of time and distance on accuracy of target-directed locomotion: Does an accurate short-term memory for spatial location exist?" *Journal of Motor Behaviour* **20** 399 – 415

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 D H, Pick H L, 1970 "Intermodality relations in localization in blind and sighted people" *Perception & Psychophysics* **8** 430 – 432

Welch R B, Warren D H, 1986 "Intersensory interactions", in *Handbook of Perception and Human Performance* volume 1, Eds K R Boff, L Kaufman, J P Thomas (New York: John Wiley) pp 25.1 – 25.36

Weiskrantz L, 1980 "Varieties of residual experience" *Quarterly Journal of Experimental Psychology* **32** 365 – 386

Werner H, Wapner S, 1955 "Changes in psychological distance under condition of danger" *Journal of Personality* **24** 153 – 167

Williams C L, Meck W H, 1991 "The organizational effects of gonadal steroids on sexually dimorphic spatial ability" *Psychoneuroendocrinology* **16** 155 – 176

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 32 2003

www.perceptionweb.com