
The contributions of static visual cues, nonvisual cues, and optic flow in distance estimation

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Abstract. By systematically varying cue availability in the stimulus and response phases of a series of same-modality and cross-modality distance matching tasks, we examined the contributions of static visual information, idiothetic information, and optic flow information. The experiment was conducted in a large-scale, open, outdoor environment. Subjects were presented with information about a distance and were then required to turn 180° before producing a distance estimate. Distance encoding and responding occurred via: (i) visually perceived target distance, or (ii) traversed distance through either blindfolded locomotion or during sighted locomotion. The results demonstrated that subjects performed with similar accuracy across all conditions. In conditions in which the stimulus and the response were delivered in the same mode, when visual information was absent, constant error was minimal; whereas, when visual information was present, overestimation was observed. In conditions in which the stimulus and response modes differed, a consistent error pattern was observed. By systematically comparing complementary conditions, we found that the availability of visual information during locomotion (particularly optic flow) led to an ‘under-perception’ of movement relative to conditions in which visual information was absent during locomotion.

1 Introduction

Humans skillfully interact with their environments on a daily basis, and, although seemingly simple, these types of interactions recruit many different sources of information. Developing a mental representation of one’s location in space requires both the visual assessment of static egocentric distance between oneself and environmental landmarks, and the continuous monitoring of dynamic distance information when traversing from one location to another. Both visual and nonvisual sources of information can potentially be used for distance processing.

Egocentric distance information can be provided by both static and dynamic visual cues. Static visual cues may include familiar retinal image size, texture gradient, accommodation, convergence, binocular disparity, etc (Foley 1980). The spatiotemporal relation between the observer and environmental landmarks is provided by dynamic retinal information generated by the observer’s self-motion (optic flow) (Gibson 1950; Lee 1980; Sun et al 1992; Warren and Hannon 1990), as well as the motion of objects in the environment (Regan and Hamstra 1993; Sun and Frost 1998).

Egocentric distance information is also available via nonvisual cues that are internally generated as a result of one’s body movements in space (Chance et al 1998; Mittelstaedt and Mittelstaedt 1980, 2001). This source of information, often referred to as ‘idiothetic information’, is provided by muscles and joints (‘inflow’ or proprioceptive input), motor efferent signals (‘outflow’), and vestibular information generated as a result of changes in linear or rotational movement velocities.

To study distance processing, researchers often use tasks that involve two components or phases—a stimulus phase and a response phase. A typical method of assessing the contribution of particular distance cues involves limiting cue availability in either of

these two phases. The distance information available in each phase could include static self-to-target distance information and/or traversed distance information obtained through self-motion.

1.1 *Tasks assessing the contributions of static visual cues and nonvisual cues*

1.1.1 *Static visual information regarding self-to-target distance.* Much research has been done to examine how humans perceive egocentric distance when assessing a target from a fixed viewpoint. In addition to laboratory studies involving the manipulation of cue availability (Foley 1980, 1991; Gogel 1990), research has been conducted to examine the visual perception of distance in natural environments under full cue conditions (Da Silva 1985). For instance, direct scaling methods, such as magnitude estimation, fractionation, and ratio estimation, have shown that perceived distance, for the most part, is linearly related to physical distance. Moreover, the accuracy of distance perception appears to depend on the psychophysical paradigm used and the range of distances tested (Da Silva 1985).

1.1.2 *Nonvisual information regarding traversed distance.* Tasks requiring the matching of two distance intervals have been used to assess the extent to which people use idiothetic information when monitoring distance travelled. For example, a common approach requires subjects to walk a distance blindfolded and subsequently reproduce this distance by again walking blindfolded (Bigel and Ellard 2000; Klatzky et al 1990; Lederman et al 1987; Loomis et al 1993; Mittelstaedt and Mittelstaedt 2001; Schwartz 1999). Similar studies conducted in a laboratory setting assessed specific aspects of nonvisual information by selectively manipulating particular cues. For example, previous studies have shown that distance learned via vestibular information generated from passive movement was accurately reproduced when participants were required to respond using the same vestibular cues (Berthoz et al 1995; Harris et al 2000; Israel et al 1997). It is important to note that in some of these studies subjects' movements were completely passive (Harris et al 2000), while in other studies subjects controlled linear self-motion without actually producing leg movements (ie via a joystick—Berthoz et al 1995; Israel et al 1997). Indeed, active control over self-movement, even when only minimal proprioceptive input is made available, has been shown to be important for processing spatial information (Sun et al, in press).

1.1.3 *Blind walking task.* One of the most influential approaches used to examine human's ability to process distance information is the blind walking task (BWT). This task requires subjects to view a target briefly in the near distance (typically less than 20 m), close their eyes, and walk without vision to the location they felt that target to have previously occupied. It has been shown unequivocally that humans are able to perform this task with reasonable accuracy (Bigel and Ellard 2000; Corlett et al 1985; Elliot 1986, 1987; Fukusima et al 1997; Loomis et al 1992; Mittelstaedt and Mittelstaedt 2001; Rieser et al 1990; Steenhuis and Goodale 1988; Thomson 1983).

It is assumed that, during this task, subjects initially encode their self-to-target distance by assessing static visual distance cues and subsequently use this visual representation to execute the appropriately scaled motor output. During locomotion, efferent and proprioceptive information are used to monitor distance as it is experienced or traversed. At the same time these cues are also used to update the internal representation of the target location (Rieser et al 1990). Overall, any errors that occur in the BWT could occur during the processing of visual information, the processing of motor information, and/or the process of visuo-motor calibration.

1.2 *Tasks assessing the contributions of optic flow*

In the BWT, subjects are required to walk a distance without vision. Such a task is a valuable tool in isolating the contributions made by idiothetic information to the process of visuo-motor coordination. However, it remains a much different task than natural

walking, in which optic flow information is typically available in combination with static visual information and idiothetic information.

Extensive research regarding the role of optic flow in visual motion, control of posture and locomotion has been undertaken in the past few decades (Gibson 1950; Lappe 2000; Warren and Wertheim 1990). This research typically employs testing paradigms involving visual stimulation of self-motion without naturally corresponding locomotor cues, thus assessing optic flow in isolation. In contrast, the integration of optic flow and nonvisual cues has only been directly explored in a limited number of studies. Such studies have involved tasks such as reproducing an angular displacement (Lambrey et al 2002); maintaining a constant walking speed on a treadmill (Konczak 1994; Prokop et al 1997; Stappers 1996; Varraine et al 2002); and path-integration tasks involving the processing of distance travelled and direction turned (Kearns et al 2002; Klatzky et al 1998).

When one navigates in an environment, optic flow can specify movement speed and overall movement magnitude (Larish and Flach 1990). Few studies have been devoted to specific examination of the role of optic flow in the estimation of distance travelled. Honeybees have been shown to use optic flow to assess distance travelled (Srinivasan et al 1996, 2000). Humans have demonstrated a similar ability when presented with computer-simulated optic flow information (Bremmer and Lappe 1999; Harris et al 2000; Redlick et al 2001; Sun et al 2004; Witmer and Kline 1998). In this context, studies have demonstrated that optic flow alone can be used to accurately discriminate and reproduce traversed distances (Bremmer and Lappe 1999). Very few researchers, however, have directly examined the role of optic flow in human navigation when the corresponding nonvisual information is concurrently available (Harris et al 2000; Nico et al 2002; Sun et al, in press), particularly with regard to locomotion in a natural setting (see Rieser et al 1995).

1.3 *The current study*

In the current investigation, we sought to understand how visual and nonvisual cues are processed during various distance estimation tasks by systematically varying cue availability. The distance information provided included (i) static visual information regarding self-to-target distance, and (ii) dynamic information regarding traversed distance generated via locomotion, either during blindfolded walking, or during sighted walking.

By extending the findings of the traditional BWT, we are better equipped to gain a clearer understanding of the mechanisms underlying the transference of information between the same and/or different modalities. Moreover, this study reveals differences that may exist as a result of discrete mechanisms involved in processing distance information when it is presented as a stimulus compared to when it is used to produce a response. In the case of the BWT, subjects first encode a visually perceived distance, which is then converted to a mental representation of that distance, which in turn leads to the resulting locomotor output. As this involves only a single combination of stimulus mode and response mode, it remains unclear where exactly these errors are occurring, as errors could occur at any stage of this process.

To examine the nature of this transformation, we compared the BWT to a condition in which the transformation was in the reverse order. In this task, subjects were required to initially travel a distance without vision and subsequently estimate this walked distance by adjusting their static self-to-target distance. If the transformation between the two modalities is stable and robust, we would expect that the constant errors typically observed in the traditional BWT and those observed in the reverse BWT would be equivalent in magnitude but reversed in direction.

Another method allowing for the identification of particular sources of error involves comparing performance in the BWT to conditions in which the transformation

of information between modalities is not necessary. In this case, either visual or motor information alone is provided in both the stimulus as well as the response phase. By examining situations in which the mode of stimulus and the mode of responding are the same, we would expect that, if these two processes (stimulus encoding and responding) are not equivalent, errors would occur as a result of the differences inherent in the two different phases. If distance estimates do in fact reflect the same internal construct, with no differences existing between the processes of encoding and responding, error would be close to zero.

Further, in addition to presenting traversed distance information in the form of nonvisual cues, an identical set of conditions in which visual information (including optic flow) is made available during locomotion is also included. The set of conditions in which visual information is not available during locomotion can then be compared to the equivalent set of conditions in which visual information is available during locomotion, thus assessing the effect of dynamic visual cues on performance.

Overall, this study is the first in which a within-subject's comparison across all possible combinations of stimulus and response modes for visual and locomotor distance cues has been conducted. Moreover, it is also the first study to formally test the contributions made by dynamic visual information to performance on several variations of the BWT. These results provide valuable insight into the underlying processes involved in distance estimation.

2 Methods

2.1 Subjects

Twelve undergraduate students (five females and seven males) with ages ranging from 18 to 21 years participated in this study. All subjects had normal or corrected-to-normal vision. All subjects received either course credit or payment for their participation, were naïve to the aim of the study, and had little or no prior experience with the testing location. This research was approved by the McMaster University Research Ethics Board.

2.2 Stimulus materials

All conditions took place in the centre of a large, open, outdoor park, approximately 200 m × 150 m in size. The ground was flat with little or no 'tactile' landmarks. No visual landmarks were present within the testing area and very few visual landmarks were present in the distant perimeter. Two-way radios combined with microphone headsets were used to communicate with subjects as they performed in each condition. These were used in order to eliminate the availability of any auditory localisation cues. A distractor task was also presented to subjects via headphones and involved making English/non-English judgments of a series of verbal phrases differing in length and varying in rhythm. Industrial earmuffs were worn to control for any other environmental auditory cues. In the conditions in which subjects were required to walk without vision, black, opaque, safety goggles were worn to eliminate all visual and directional light cues. Distances were measured with a retractable tape measure. A human target was chosen in order to provide subjects with a familiar frame of reference and account for effects of familiar size constancy. The distances used for testing were 10, 15, and 20 m, and target distances were pre-measured and discretely marked with coloured golf tees that were not visible to subjects throughout the experiment.

2.3 Procedure

All conditions involved presenting the subjects with a target distance when facing one direction of the field and having them turn 180° before responding with their distance estimate. Before beginning the experiment, subjects completed five practice trials without feedback in order to ensure that they were comfortable walking without vision and that they were proficient at using the two-way radios to communicate. For all conditions in

which subjects traversed a distance, one of the experimenters walked beside the subject, lightly grasping his/her elbow to correct for veering and to increase comfort levels. The experimenter was very careful in maintaining the same walking pace so as not to influence the subject's estimates with own movements or expectations. Subjects were blindfolded before being guided to the starting position of each trial. In conditions in which subjects were required to walk with their eyes open it was requested that they keep their head facing forward and they were explicitly asked not to look at the ground. On average, subjects travelled at a speed of approximately 0.7 m s^{-1} .

During the stimulus phase, distance was specified by one of two modes: (i) static visual information regarding self-to-target distance (V), (ii) dynamic information regarding traversed distance generated via locomotion either during blindfolded locomotion (L) or during locomotion with vision (Lv). During the response phase, subjects reproduced their distance estimates via one of these same two modes (V and L or Lv) and subjects were given as much time as they required to produce their estimates. Table 1 illustrates all possible permutations for V and L (table 1a) and V and Lv (table 1b), resulting in a total of 7 conditions, considering that the V–V condition was repeated.

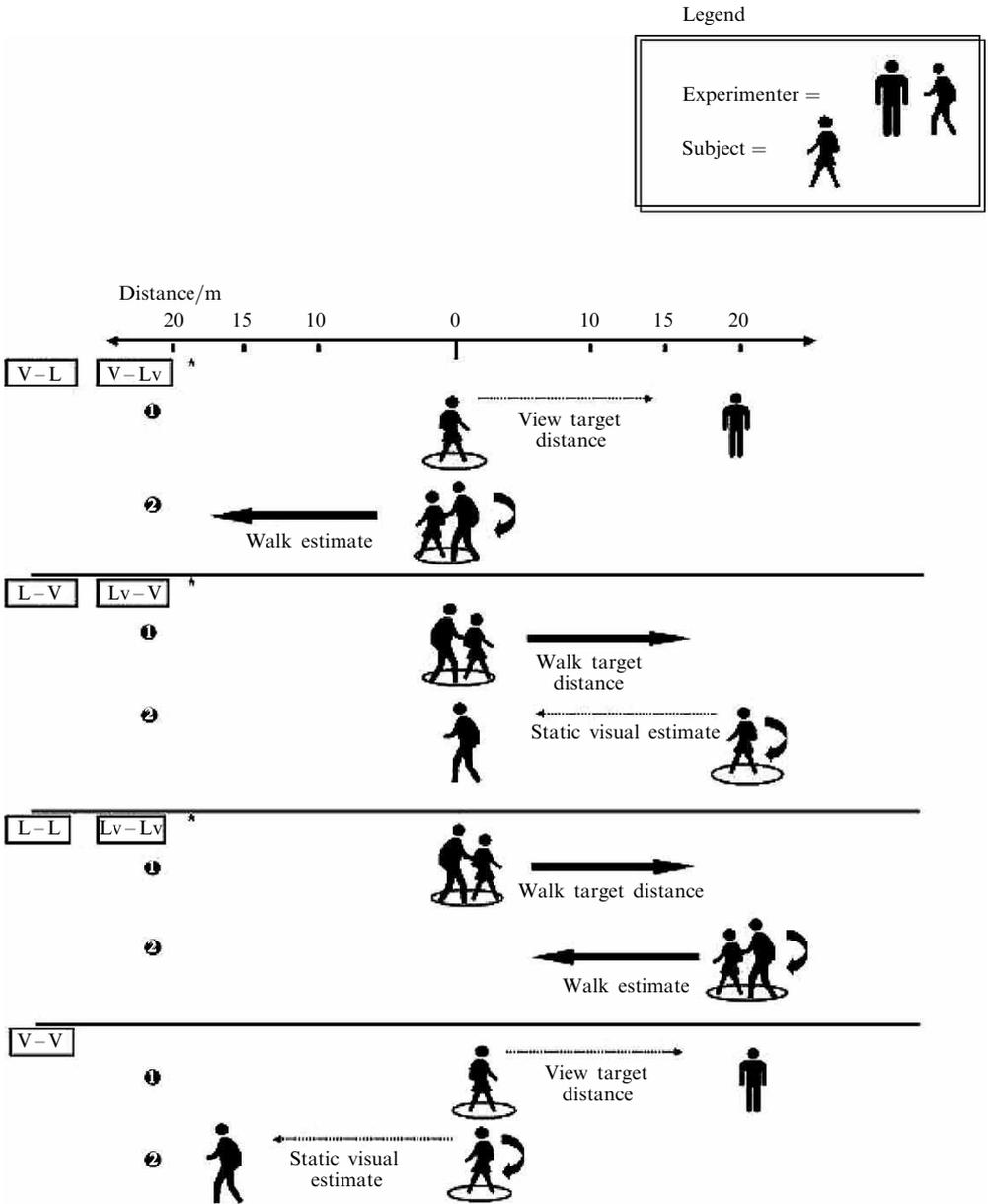
Table 1. (a) A summary of the permutation of cue combinations: static visual cues and locomotor cues. (b) A summary of the permutation of cue combinations: static visual cues and combined optic flow cues and locomotor cues.

(a) Response mode	Stimulus mode		(b) Response mode	Stimulus mode	
	V	L		V	Lv
V	V–V	L–V	V	V–V	Lv–V
L	V–L	L–L	Lv	V–Lv	Lv–Lv

Figure 1 illustrates the procedures for all conditions. All subjects completed all conditions in a random order. The V–L condition was basically a replication of the traditional BWT whereby subjects viewed a target in the distance, turned 180° , and walked blindfolded to a location they felt matched the target distance. The L–V condition was a reversal of the traditional BWT whereby subjects walked a distance blindfolded (were verbally instructed to stop over the headphones), turned 180° , and relying on static visual cues, verbally positioned the target to a location representing the distance they felt they had just walked. In the V–V condition, subjects viewed the target in the distance, turned 180° , and, relying on static visual cues, verbally positioned the target to a location representing the distance they had just viewed. In the L–L condition, subjects were required to walk a distance blindfolded, turn 180° , and walk that same distance in the opposite direction blindfolded (see table 1a).

The remaining 3 conditions were equivalent to the conditions mentioned above (excluding V–V), the only difference being that visual information was available during locomotion. The V–Lv condition was basically the same as the traditional BWT, with the exception that, after visually previewing the target in the distance and turning 180° , subjects walked with vision to a location they felt represented the originally viewed target distance. The Lv–V condition was the equivalent of a reversed BWT, with the exception that subjects walked a distance with vision, turned 180° , and then positioned a target to a location representing the distance they had just walked. Finally, the Lv–Lv condition required subjects to walk a distance with vision, turn 180° , and reproduce that walked distance in the opposite direction with vision (see table 1b).

Each condition consisted of 9 trials, each comprising 3 repetitions of 3 distances (10, 15, 20 m) presented in a random order.



* In the marked conditions, subjects were either blindfolded or were provided with optic flow information.

Figure 1. An illustration of the procedures of all 7 conditions.

3 Results

Variable errors, constant (signed) errors, and absolute (unsigned) errors were calculated. Variable error is defined as the standard deviation of the distance responses across 3 repetitions. Variable error corresponds to the precision with which distance is estimated across trials and reflects the variability with which subjects respond. Constant error corresponds to the accuracy with which distance is estimated, defined as the averaged signed error (across 3 repetitions), and reflects the tendency for subjects to either underestimate or overestimate the target distance. Absolute error is the averaged unsigned error (across 3 repetitions), and reflects the overall magnitude of error.

3.1 Variable error

A repeated-measures ANOVA (7 conditions \times 3 distances) was conducted on variable error, demonstrating no significant difference across the 7 conditions. However, there was a significant difference when comparing across the 3 distances ($F_{2,22} = 3.50$, $p < 0.05$), with variable errors typically increasing with increasing distance (see figure 2).

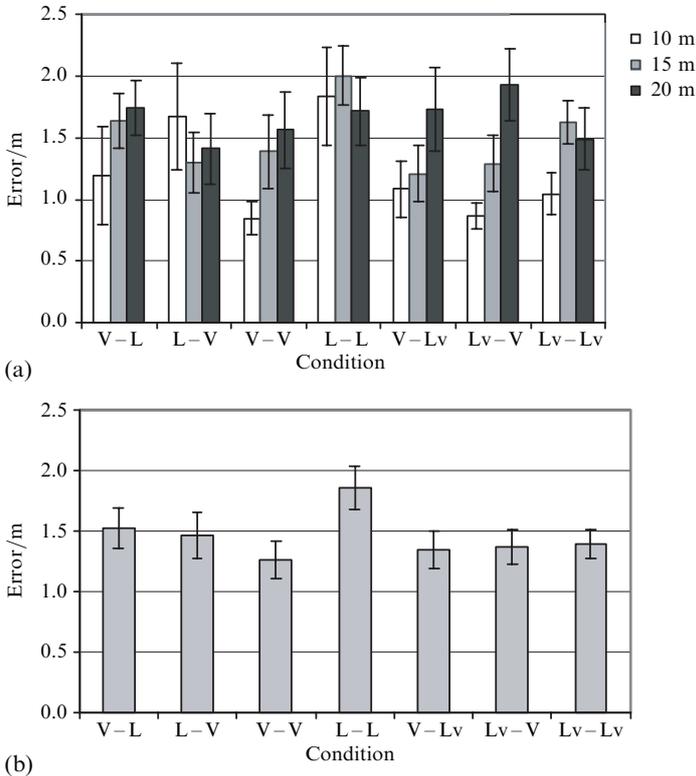


Figure 2. (a) Overall variable error by distance. (b) Overall variable error collapsed across distances.

3.2 Constant and absolute errors: individual distances

Constant errors were small in all conditions indicating reasonably good performance overall (see figure 3). We first examined how constant error varied as a function of condition and distance. A repeated-measures ANOVA (7 conditions \times 3 distances) was conducted on constant error, indicating a significant main effect of condition ($F_{6,66} = 9.34$, $p < 0.05$), as well as a significant main effect of distance ($F_{2,22} = 7.99$, $p < 0.05$). There was also a significant interaction effect between condition and distance ($F_{12,132} = 5.11$, $p < 0.01$). However, a careful examination of the interaction effect revealed that, with the exception of the V-V and L-L conditions, in the remaining 5 conditions, the constant errors became more negative as distance increased (figure 3a). In fact, the results of an additional repeated-measures ANOVA (5 conditions \times 3 distances) conducted on the constant error following the removal of the V-V and L-L conditions, indicated no significant interaction between condition and distance. This suggests that the pattern of variation observed between the 3 distances was maintained across all 5 conditions. Thus, the relative difference in errors between conditions was similar for each of the 3 distances. Consequently, the pattern of error observed when the 3 distances were combined should reflect the same pattern of error observed when each distance is analysed independently.

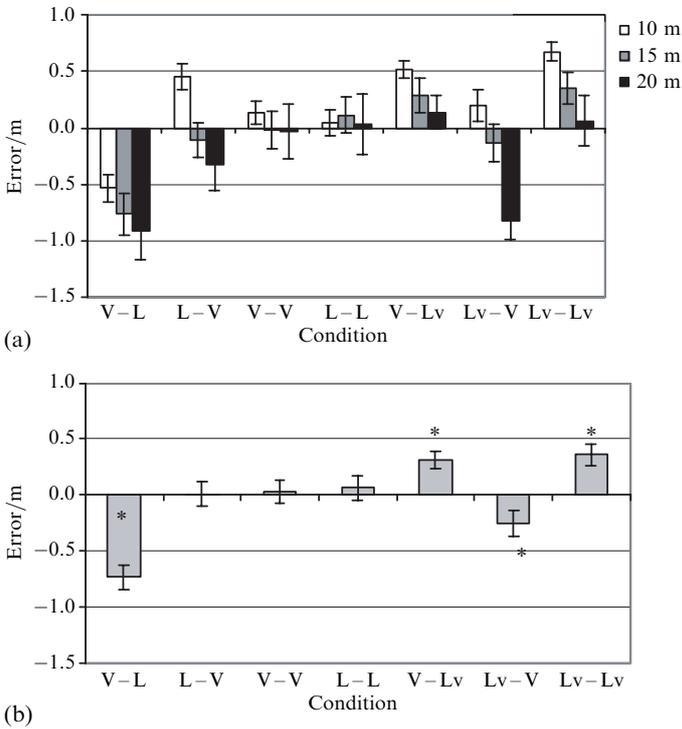


Figure 3. (a) Overall constant error by distance. (b) Overall constant error collapsed across distances. Stars represent constant errors that are significantly different from zero.

3.3 Constant and absolute errors: combined distances

In order to establish whether constant error in each individual condition is a true reflection of systematic errors, a series of t -tests was conducted to assess whether the overall constant errors found in each condition were significantly different from zero. The conditions in which average constant error deviated significantly from zero included the following: V-L ($t_{1,35} = 6.59$, $p < 0.05$), V-Lv ($t_{1,35} = 3.97$, $p < 0.05$), Lv-V ($t_{1,35} = 2.23$, $p < 0.05$), and Lv-Lv ($t_{1,35} = 3.66$, $p < 0.05$).

In addition to examining whether subjects systematically underestimated or overestimated distances in each individual condition, it is imperative to compare the results found in complementary conditions rather than to simply examine each condition independently. In particular, we compared: (a) conditions in which the stimulus and response modes were the same as those in which the two modes were different; (b) each condition to their reversed counterparts; and (c) conditions in which visual information was available during locomotion to equivalent conditions in which visual information was not available during locomotion.

Following the significant main effect of condition as reported above, a series of planned pairwise comparisons was conducted in order to directly compare particular stimulus/response mode combinations to further isolate the sources of error.

3.3.1 Same-modality matching conditions. Based on comparisons between the 3 ‘same’ conditions, it appears as though this pattern of error varied as a function of whether or not visual information was made available during locomotion (figure 3b). Constant error observed when visual information was available (Lv-Lv), was larger than the combined error of V-V and L-L. This difference approached significance ($F_{1,11} = 4.45$, $p = 0.059$). In fact, with regards to all of the same-modality matching tasks, only Lv-Lv was significantly different from zero ($M = +0.36$ m), whereas the errors for both V-V

and L–L were minimal and not significantly different from zero (indicating accurate performance). The comparison between L–L and Lv–Lv was also marginally significant ($F_{1,11} = 4.81$, $p = 0.051$), with the difference between the two equaling 0.30 m (0.36 m–0.06 m).

3.3.2 Cross-modality matching conditions. When different sensory modalities were involved in the stimulus and response phases (V–L versus L–V, and V–Lv versus Lv–V), the pattern of errors varied in both direction and magnitude.

First, in order to test whether or not the phase during which a particular sensory cue was experienced (stimulus or response) affected performance, a comparison was conducted between conditions that were the reverse of each other. In terms of absolute error, a marginally significant difference was found when comparing the traditional BWT (V–L) to the reversed BWT (L–V) ($F_{1,11} = 4.56$, $p = 0.056$), with subjects significantly underestimating in the V–L condition. However, no significant difference was found when comparing absolute error in the V–Lv condition to the reversed condition (Lv–V) ($F_{1,11} = 1.175$, $p > 0.05$), demonstrating a similar magnitude of error but opposite in direction (overestimated in V–Lv and underestimated in Lv–V).

3.3.3 Effect of visual information during locomotion. In order to assess the effect that visual information had on performance, direct comparisons were made between conditions in which visual information was not available during locomotion and the equivalent conditions in which it was available. When comparing constant error in the traditional BWT (V–L) to the equivalent condition with the addition of visual information during locomotion (V–Lv), a significant difference was observed ($F_{1,11} = 28.7$, $p < 0.001$), with the difference between the two equaling 1.05 m [0.32 m – (–0.73 m)]. The comparison between L–V and Lv–V was marginally significant ($F_{1,11} = 4.53$, $p = 0.057$), with the difference between the two equaling –0.26 m [(–0.25 m) – 0.01 m]. In each of these cases, subjects significantly overestimated distance in conditions in which visual information was made available during the response phase (V–Lv as opposed to V–L) and significantly underestimated distance when visual information was available during the stimulus phase (Lv–V as opposed to L–V).

4 Discussion

Although we typically use multiple, concurrently available cues to accurately navigate through our environments, we are also able to perform well in situations in which the availability of particular cues is limited. The results of this study confirm this supposition, demonstrating that we are able to extract information about distance from one modality and accurately respond in either the same or a different modality. In addition, we are able to calibrate perception with action and action with perception.

Although constant errors in these tasks were small, because these conditions were tested in the same open environment with comparable stimulus conditions and the same subjects, these errors serve as sensitive and informative measurements. In fact, certain systematic trends or regularities in error patterns were observed between conditions and between distances. It is important to acknowledge that the most valuable information comes from comparing the relative differences observed between conditions (for the same distance) as opposed to the errors observed in individual conditions.

The constant errors observed in the V–V and L–L conditions were close to zero for all 3 distances. For each of the 5 remaining conditions, the 3 distance estimates could have resulted in either an overshoot (positive error) or an undershoot (negative error), but in relative terms between the 3 distances, errors were always ‘more positive’ for shorter distances compared to longer distances (figure 3a). For example, for the V–L condition, at distances of 10 m, 15 m, and 20 m, constant errors were –0.51 m, –0.72 m, and –0.95 m, respectively. Therefore, as distance decreased, error became

increasingly positive, even though all 3 distances reflected negative constant errors. This trend observed across the 3 distances remained quite consistent for all 5 conditions and thus, for simplicity, the discussion will focus on the averaged response across all 3 distances.

The error trend across distances resembled the 'range effect' or 'central tendency effect', such that subjects tended to overshoot shorter distances and undershoot longer distances. This range effect has been found in studies of distance estimation both in a natural environment (eg Rieser et al 1990; Steenhuis and Goodale 1988), and in laboratory settings involving passive physical movement (Berthoz et al 1995; Israel et al 1997) and involving simulated motion specified by optic flow (Bremmer and Lappe 1999).

5 Same-modality matching tasks

The visual matching task (V-V) included in this study was modelled after a previously developed bisection task, which involved judging a self-to-target midpoint by adjusting the position of a target (Rieser et al 1990). Our visual matching task was designed to allow for a more direct comparison with the BWT by requiring a comparison between 2 distances of the same scale rather than distances of different magnitudes (Rieser et al 1990). Further, the 2 distances were presented in a sequential manner instead of being viewed simultaneously (Rieser et al 1990).

Rieser et al (1990) found that the variable errors observed in the bisection task were much smaller than those observed in the BWT. In light of this, Rieser et al concluded that, with regard to the BWT, the processing of static information is most likely not the major source of variable error. In our study, although the variable errors observed in the V-V condition appeared to be smaller than those observed in the V-L condition (BWT), this difference was not statistically significant. The differences in the magnitude of variable error observed between these two studies could be partially due to the procedural differences inherent in Rieser et al's bisection task compared to our visual matching task. The smaller variable errors reported in their task could relate to the fact that subjects were required to produce a distance estimate representing half of the actual target distance. With this in mind, it is important to note that smaller distances led to smaller variable error, thus perhaps explaining the discrepancy.

The minimal constant error observed in the V-V condition in our study is consistent with the low constant errors reported by Rieser et al (1990). Similarly, the minimal constant error observed in our L-L condition is consistent with the findings reported in a number of other studies in which similar procedures were used (Klatzky et al 1990; Lederman et al 1987; Loomis et al 1993; Mittelstaedt and Mittelstaedt 2001; Schwartz 1999).

The minimal constant errors found in both the V-V and L-L conditions suggest that subjects were able to build an internal representation of the perceived or traversed distance, and, using this representation, were able to accurately reproduce the originally learned distance by using the same sensory modality. However, such tasks by themselves do not directly inform us whether such internal representations of distance were true to the real physical distance. In theory, it remains possible that subjects' internal distance representations do not reflect the true physical distance and may be expanded or compressed. When subjects are required to produce a distance estimate using information from the same modality in which it was learned, these errors could essentially cancel each other out and thus would not be revealed.

With this in mind, the pattern of constant errors observed in these tasks is still valuable when attempting to determine whether information is processed in the same way regardless of whether it occurs in the stimulus phase or the response phase (Israel et al 1997). The minimal constant errors observed in the V-V and L-L conditions suggest that, in these two conditions, the information was processed in the same way regardless of whether it was available in the stimulus phase or in the response phase.

Interestingly, in the Lv–Lv condition, a positive constant error was observed. This overshoot is consistent with previously reported results of studies in which subjects were provided exclusively with optic flow information (Bremmer and Lappe 1999). Bremmer and Lappe found that subjects slightly overestimated distance when required to reproduce the magnitude of a passive forward motion trajectory. To reproduce a travelled distance specified by optic flow, their subjects controlled their movement by adjusting the pressure applied to a hand-controlled isometric force detector.

It is possible that the overestimation observed in distance reproduction tasks involving sighted locomotion may reflect differences inherent in how information is processed in the stimulus phase compared to the response phase—otherwise referred to as ‘stimulus–response specificity’. In other words, the task requirements or processes involved in learning a distance may be different from the processes involved in producing a distance estimate under certain stimulus conditions.

When presented with a traversed distance via locomotion during the stimulus phase, subjects were led by the experimenter to walk until indicated to stop, and consequently had no way of anticipating the end of the path or pre-planning goal-directed movements. In contrast, during the response phase, subjects were able to *actively* perform the motor act, including pre-planning their desired motor behaviour, while retaining complete control over the magnitude of their walked distance. Consequently, such an ‘active’ factor may have exerted more influence during the response phase compared to the stimulus phase. Such a stimulus–response specificity effect resulting from the active nature of the response phase has previously been addressed when comparing performance on visually directed locomotion tasks to those on triangulation tasks (Philbeck et al 2001).

In our experiment, a stimulus–response specificity effect was only observed in conditions in which visual information was available during locomotion. When comparing the results of the Lv–Lv and L–L conditions, the only difference between the two was the presence or absence of visual information. The fact that a significant constant error was present in the Lv–Lv condition but absent in the L–L condition, suggests that the availability of visual information during locomotion, together with the active nature of the task, may have led to the observed stimulus–response specificity effect.

6 Cross-modal matching tasks

The most striking demonstration of subject’s ability to estimate absolute distance is revealed through conditions in which distance information in the stimulus phase and in the response phase involved different modalities (eg BWT). Although the errors in cross-modality matching conditions were typically larger than in the same-modality matching conditions, errors were still relatively low overall. This suggests that subjects were able to build an internal representation of the perceived or traversed distance and using the same scale, generate the corresponding motor or visually specified output.

When the visual preview of a target distance was followed by idiothetic estimation without vision (V–L), underestimation was found. The size of the constant and variable errors observed here is comparable to the errors generally reported in the BWT literature (Bigel and Ellard 2000; Corlett et al 1985; Elliott 1986, 1987; Fukusima et al 1997; Loomis et al 1992; Mittelstaedt and Mittelstaedt 2001; Rieser et al 1990; Steenhuis and Goodale 1988; Thomson 1983).

6.1 Locomotion without visual information

During cross-modality matching tasks, separate errors may occur during the processes of perceiving the visual target distance, updating the proprioceptive information obtained through movement in space, and/or during the transformation of information from one modality to another. Assuming that the transformational process is unchanging,

if the stimulus and response modes were reversed (L–V to V–L), this should result in constant errors that are the same in magnitude but opposite in direction. In other words, because we observed a significant underestimation (negative constant error) in the V–L condition, symmetry would predict positive constant error values of the same magnitude for the L–V condition. In contrast, the L–V condition produced minimal constant error. This suggests that the transformation of a visual input to a proprioceptive output (V–L) produces errors that differ from those produced following the opposite transformation (L–V).

The asymmetry of errors observed here could be due to intrinsic differences in the internal representations of space following exposure to visual information versus exposure to idiothetic information. It has been proposed that visual information facilitates the formation of mental representations of space (Philbeck et al 2001). If the visual information is presented in the stimulus phase of the condition, as is the case in the V–L condition, this may facilitate the overall processing. However, if it is only available during responding, as is the case in the L–V condition, such a beneficial effect may not occur. In other words, locomotor activity following a visual preview may be processed differently than locomotor activity without the benefit of any preceding visual information.

Although it may appear that human subjects perform the BWT by coordinating their motor output with a visually perceived distance, the small delay interposed between the visual presentation and the motor response, along with the fact that the walk is an open-loop response, may indicate that action is only indirectly linked to the visual percept. The precise magnitude of motor output may be a result of compensatory learning mechanisms (Philbeck 2000), such that perception and action may be differentially related to the physical stimulus. Indeed, it is well known that the visual perception of distance tends to lead to underestimation (Loomis et al 1992; Norman et al 1996; Philbeck 2000; Wagner 1985). Such conclusions are drawn from visual matching tasks that require subjects to adjust the magnitude of one distance interval, orientated either in a frontoparallel plane or in-depth, to match another interval orientated in the other direction. It was observed that subjects severely underestimated distance intervals when they were oriented in-depth compared to when they were oriented in a frontoparallel plane (Loomis et al 1992; Norman et al 1996).

A number of mechanisms have been proposed to account for the differences involved in visually directed action and those involved in the visual perception of distance and shape in-depth (Loomis et al 1992, 2002; Philbeck 2000). For example, it is possible that while visual perception leads to systematic errors resulting in the foreshortening of distance, visually directed action may be able to compensate for this via learning (Rieser et al 1990). Over one's lifetime, the correlation between visually specified distance and the magnitude of the action required to traverse that distance is well learned. Alternatively, the correlation between action and visual distance may be a specialised feature of visual pathways that are dedicated to control of movement (Milner and Goodale 1995). Such a mechanism for vision-for-action may not be revealed in the same way in the L–V condition and in the V–L condition, owing to the fact that the locomotor activity in the L–V condition is not visually directed, whereas the locomotor activity in the V–L condition is.

6.2 *Locomotion with visual information*

In conditions involving sighted locomotion, there are a number of visual cues that may potentially contribute to distance estimation—the most obvious being static visual cues and optic flow information. Although we are unable to precisely quantify the contributions made by each cue, there are a number of reasons suggesting that the presence of optic flow does in fact influence performance. For instance, by having subjects turn

180° before producing a response, this eliminates the possibility that their responses are directed to particular static visual landmarks, therefore limiting the visual cues available during the response phase to optic flow. That said, even when the subjects face the opposite direction, it remains possible that they choose a goal location corresponding to the distance presented in the stimulus phase prior to producing their response, somewhat reminiscent of a static visual matching task (ie V–V). However, because subjects were required to walk facing forward and were asked not to look at the ground, any location that may have been visually tracked by the subject would become ineffective, as it would eventually disappear from their field of view upon approach. Further, although there were static distal landmarks surrounding the perimeter of the testing environment that could potentially have served as cues, they were located a substantial distance away (100 m), thus remaining unreliable as perceptual cues. In fact, should subjects have attempted to use such cues, it would be expected that the overall variable error would have been much greater than what was actually observed in our study.

Empirical evidence further supports the contention that specific contributions are made by optic flow to the process of distance estimation. We would predict that, when comparing the results of conditions involving solely static visual cues (V–V) to conditions involving full visual cues (V–Lv), if subjects simply relied on static visual cues and dismissed optic flow information, performance in these two conditions would be practically identical. This was in fact not the case, thus identifying optic flow as the logical source of the observed differences. Overall, on the basis of reasons discussed above, we believe that during sighted locomotion optic flow remains a significant source of visual information.

In the current experiment, when subjects were required to learn a visually perceived static target distance and respond by traversing the equivalent distance with vision (V–Lv), an overestimation was observed. These results are consistent with similar findings observed in a virtual environment, demonstrating that when subjects were required to match a distance specified exclusively by optic flow information to a visually perceived static target distance, a slight overestimation was observed (Harris et al 2000).

In addition to analysing the errors for individual conditions separately, performance in conditions in which visual information was available during locomotion is most informative when compared to the equivalent conditions involving blindfolded locomotion. When visual information was available in the response phase, such as in the V–Lv condition, subjects significantly overshoot the actual distance (+0.30 m) compared to the identical condition without visual information (V–L) in which subjects significantly undershot the actual distance (–0.70 m). Combined, this amounts to a difference in error of about 1.0 m, which can be attributed to the presence of visual information in the response phase.

Conversely, when sighted locomotion occurred in the stimulus phase, such as in the Lv–V condition, subjects significantly undershot the actual distance (–0.25 m) compared to the equivalent condition involving blindfolded locomotion (L–V) in which errors were minimal (0.01 m). Combined, this amounts to a difference in error of –0.26 m, which can be attributed to the availability of visual information in the stimulus phase.

The overall amount of constant error that can be accounted for by visual information is approximately 1.0 m when available in the response phase and –0.26 m when available in the stimulus phase—a difference of 0.74 m. This suggests that should visual information be available in both phases, an overestimation of approximately 0.74 m would be observed. This is somewhat consistent with what was observed in the Lv–Lv condition (an overestimation of 0.3 m).

In general, for cross-modality matching tasks, results appear to suggest that, overall, when walking with vision, subjects ‘under-perceived’ the locomotion magnitude. When visual information was available in the response phase, subjects felt as though they needed to walk further than was actually necessary to reach the true target distance. Conversely, when visual information was available in the stimulus phase, subjects under-perceived the distance they had travelled and thus produced a static, visually specified estimate that was shorter than the actual target distance.

The above claim regarding the ‘under-perception’ of movement extent in locomotion with visual information is made through comparing distance estimates with the actual physical distances, that is constant errors described in absolute terms (positive or negative) within each individual condition. Moreover, the *relative* under-perception of movement extent is also true when we compare the conditions involving sighted locomotion to the corresponding blindfolded conditions. In fact, considering that visual information is normally available to us during locomotion, it is more reasonable to consider that, when visual information was absent during locomotion, there was a relative *over-perception* of movement in which subjects felt as though they had moved further than what they would normally perceive if they had their eyes open. This over-perception of movement observed during blindfolded walking may be related to spatial distortions produced by an implicit defense mechanism which causes subjects to act with extra caution during locomotion without vision (Nico et al 2002; Werner and Wapner 1955).

6.3 *The relative contributions of optic flow and idiothetic information during sighted locomotion*

Previous studies have shown that optic flow information alone is sufficient for estimating traversed distances relative to distances specified by a static target (Harris et al 2000) and also for distance reproduction (Bremmer and Lappe 1999). Our study has shown that subjects were able to perform the same two sets of tasks with reasonable accuracy with either idiothetic information alone or when in combination with dynamic visual information. Taken together, it appears that dynamic visual information (presumably optic flow) and idiothetic information, presented alone or in combination, leads to similar performance, indicating that some degree of redundancy exists during normal sighted locomotion.

In our study, although general performance levels were found to be similar, with or without visual information, some consistent patterns related to the presence of visual information were apparent, indicating an effect, although small, of dynamic visual information when nonvisual information was also present.

Harris et al (2000) used a virtual-reality setup to investigate the relative contributions of optic flow and vestibular information to the estimation of distance travelled during passive linear self-motion. Subjects were required to match a traversed distance, as indicated by optic flow information, passive physical motion in the dark, or a combination of both, with a stimulus distance presented via either a static visual target or via physical motion in the dark. They found that performance was accurate when the task was to match distance indicated by optic flow to perceived static target distance and when the task was to reproduce a traversed distance indicated by physical motion in the dark. Large errors were reported in the cross-modal matching conditions included in Harris et al (2000), which contrasts with the small errors observed in our cross-modality matching conditions. Due to the fact that the design used by Harris et al (2000) did not incorporate proprioceptive information, the large errors in the cross-modality matching task speak to the importance of proprioceptive information in monitoring extent of movement.

Harris et al (2000) also found that when the response phase consisted of a traversed distance specified by both optic flow and vestibular cues, the response patterns more closely resembled those observed when the response phase consisted of a traversed

distance specified by vestibular cues. This suggests that vestibular cues contribute to a greater extent to distance estimation than does optic flow information. The fact that nonvisual information has a strong effect on performance, even with the removal of proprioceptive information, demonstrates the strength of its influence.

However, these results do not exclude the possibility that optic flow plays some role in estimating the extent of self-motion. The role of optic flow when nonvisual information is available can best be revealed by using a cue-conflict paradigm to assess overall relative cue weighting. A small but significant effect of optic flow was observed in a series of studies employing treadmill-walking tasks (Konczak 1994; Prokop et al 1997; Stappers 1996; Varraine et al 2002). For instance, Prokop et al (1997) conducted a study in which subjects were instructed to walk at a constant speed on a closed-loop treadmill, while the magnitude of optic flow was manipulated. Their results demonstrated that subjects modulated their movements in response to variations in optic flow magnitude. However, the degree to which subjects modified their movements was far less than predicted if subjects relied on optic flow only.

The effect of optic flow on distance estimation has also been demonstrated through the employment of cue-conflict paradigms. In order to study visual and nonvisual interactions during locomotion in a real-world environment, Rieser et al (1995) attempted to uncouple the natural covariance of optic flow and proprioception. Subjects were asked to walk on a treadmill at one speed (biomechanical feedback) while being pulled on a tractor at either a faster or a slower speed (environmental flow feedback). Subjects' distance estimations were altered after they experienced a new relation between locomotor activity and the resulting optic flow.

In summary, this study, by comparing multiple stimulus-response pairs and by testing within the same subjects, revealed many interesting aspects of the processes involved in perception-action calibration. This was the first study to demonstrate that subjects perform with similar accuracy with or without dynamic visual information in a modified BWT. By systematically comparing complementary conditions, the results showed that the availability of dynamic visual information, presumably optic flow, leads to an under-perception of movement relative to conditions in which optic flow is absent. Consequently, the results of these tasks help elucidate the underlying mechanisms involved in the encoding and transfer of different sources of information, thus gaining insight into how humans process egocentric distance information.

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