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The estimation of distance, direction and self-position through non-visual locomotion.

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ABSTRACT

Five experiments examined the accuracy with which individuals could utilize visual and non-visual sensory information to either return to, point towards or verbally estimate the distance and direction to previously learned targets. Gender differences in spatial performance were also explicitly evaluated. All five experiments indicated that prior visual information about a target's location facilitated accurate performance and showed that gender differences exist for perceptual spatial tasks but disappear when performance is evaluated. Non-visual performance was more variable but the errors generated in experiments 1, 2 and 3 revealed that both the direction and the distance of a target might be determined with some accuracy using non-visual information. Whether participants pointed or walked to a named target, experiment 4 showed that prior vision enabled them to maintain the integrity of their representations of space after they were led without vision to a novel location. <u>Walking</u> heading was more accurate than <u>pointing</u> heading for participants in the non-vision group of this experiment. We postulated that accurate pointing was related to the intimate link between the eye-head-arm system and might be affected by manipulating retinal and extra-retinal cues. Altering the congruence of retinal and extra-retinal signals in experiment 5 did not significantly influence pointing or walking performance. Overall, performance accuracy appeared to depend on whether the response output used was pointing, walking, map drawing or a verbal report. The results suggest that there is not one central representation of space that each response system may tap into but that each response output likely employs separate representations of space that are governed by different rules.

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INTRODUCTION

Studying human navigation is neither simple nor straightforward. Without the knowledge of what goes on at the neuronal level, inferences about how the brain processes spatial information for navigation must be formulated by examining overt behaviour, namely performance in the real world. Being able to find the way back to a previously visited place is important for everyday human behaviour, and vision generally provides a traveler with enough information about the world to accomplish this task. But, because navigation accuracy is not determined by visual information alone, it is important to understand the contribution made by senses other than vision. Researchers in human navigation have been interested in understanding how non-visual information (e.g. vestibular, somatosensory) is processed for the estimation of distance and direction. Being able to accurately estimate distance and direction is the first step to accurate navigation. Although there are a handful of good studies on this topic (e.g. Klatzky et al. 1990; Loomis et al. 1993; Rieser et al. 1986), the study of non-visual navigation in humans is not particularly extensive.

Much of what is known about navigation behaviour has come from the extensive literature on animals ranging from ants and bees to birds, rodents and dogs (e.g. Wehner, 1981; Cartwright and Collett, 1983; Cheng, 1988; Beritoff, 1965; Gallistel, 1990; Etienne et al., 1990). It has been shown, quite convincingly, that animals are capable of solving relatively simple, short-distance navigation problems in a number of different ways using limited sensory information (e.g. Etienne et al., 1993; Collett, Cartwright and Smith, 1986; Cheng, 1989). Presumably humans are just as capable of solving simple navigation problems by employing similar strategies but studying navigation behaviour in humans is different from examining it in animals because humans use strategies that we know animals cannot use. For instance, humans can learn to navigate by following explicit directions but it takes animals many trials to learn a similar type of task. Despite this important distinction, studies of animal navigation have inspired many studies of human navigation and have provided a methodological basis from which human navigation may be explored.

Navigation Strategies and the Spatial Information Required for Navigation

The type of spatial information available to an individual at the time of travel is important as it is related to the accuracy with which a spatial task like short distance navigation or distance and direction estimation may be accomplished. There are two main sources of spatial information that can be used for these spatial behaviours. We may use information from the location of landmarks as well as information about other spatial properties intrinsic to the environment, like its geometry. As a general rule, this information is acquired visually, although audition and somatosensation might also provide such information. Moreover, one may acquire this information while standing still or moving (Gibson, 1979). The second source of information we may use to solve navigation-related behaviours is that which is acquired from locomotion within the environment. This information is derived from sensations originating from the vestibular, kinesthetic and somatosensory systems. However, it is also true that this information may be acquired while walking through an environment with the full availability of vision. The key distinction here is that when vision is <u>unavailable</u>, these systems likely provide the only sources of spatial information for navigation. When visual information is available during locomotion, it is used preferentially to provide accurate information about external references such as landmarks, and thus provides a traveler with enough information to solve simple navigational tasks (Thinus-Blanc and Gaunet, 1997). In the absence of vision the information required to estimate the distance and the direction from a point of origin to the final point of a movement path must be internally derived through self-generated movements like locomotion (Etienne, Maurer and Seguinot, 1996). Information from the vestibular and somatosensory systems along with stored motor efference copy signals (a copy of the motor command or "outflow" signals) provides most navigational information during locomotion without vision.

What contributes to the challenge of non-visual navigation is the fact that there is usually both a translational (i.e. linear distance) and rotational (i.e. directional) component to locomotion that must be encoded and perceived; position in space cannot be estimated from either component alone (Etienne et al., 1996). Theoretically, knowing the direction, the velocity and the duration of travel, one can calculate the distance traveled. Using slightly more complex calculations one can also estimate position. As mentioned earlier, the vestibular system makes a contribution to our ability to navigate in the absence of vision. The vestibular apparatus of the inner ear is capable of detecting changes in linear and angular velocity of the head. To estimate the distance one has traveled, multiplying the velocity by the duration of travel will suffice, providing velocity is known. But, because the vestibular system only detects changes in velocity, if velocity is not known, position may not be determined solely by the vestibular system. If information about velocity values can be obtained from other senses or through other means (e.g. by an organism keeping track of its velocity after each change in velocity it makes), it could determine actual distance traveled (i.e. final position). In a complex journey that involves changes in speeds and directions, double integrations of linear and angular velocities may be calculated to keep track of position (Potegal, 1982). Along with the vestibular system, the somatosensory system stores motor (motor efference copy) and proprioceptive information generated by the trunk and legs during locomotion. Information from these two systems is further synthesized by the central nervous system (CNS) to allow an organism to update current position relative to the previous position (see Barlow, 1964; Wiener and Berthoz, 1993). This updating process is continuous throughout movement. It is believed to be more accurate over short distances, is subject to cumulative error over longer distances (Barlow, 1964; Potegal, 1982) and is considered to be the means by which both humans and animals navigate. This method of navigation has been referred to as *path integration*, *dead reckoning*, (Etienne et al. 1996; Gallistel, 1990), *idiothetic navigation* (Mittelstaedt and Mittelstaedt, 1980) and *inertial navigation* (Barlow, 1964). Although subtly different definitions of these navigational methods have been put forth, the terms are interchangeable and there is no strong consensus on the specific differences between them. For instance, the term dead reckoning may have been derived from deduced reckoning (Gallistel, 1990) and this type of navigation is commonly used aboard ships where the last known position, course heading, speed and elapsed time since the last position are variables used to compute current position (Schisser, 1986). Path integration is defined as the process of integrating the linear and angular velocity components that are based on linear and angular displacements as a result of locomotive travel. An organism is able to estimate its position at the end of a movement path by keeping track of its own movements with respect to the origin (Maurer, 1998). In more behavioural terms, path integration has been defined as the ability to return to the origin of travel in the absence of external information about location. If a traveler can path integrate, that is, update their position with respect to a known point of origin after walking without vision, then presumably the traveler could similarly estimate the distance and direction they had traveled in order to return to that point of origin. Although path integration is classically defined as the ability to return to the point of origin of travel, another location in space may be substituted for the preferred point of return without diminishing the validity of the principle or changing the concept.

Visual Contributions to Non-Visual Navigation

In an often-cited study, Thomson (1980, 1983) studied whether continuous visual input was necessary for the accurate control of locomotion or whether previously sampled visual information was sufficient. Thomson asked his participants to view a distant visual target for approximately 5 seconds and then asked them to walk, with closed eyes to the location of the target. The targets ranged from 3 to 21 meters (at 3 m intervals) from the starting position and there were no other distance cues available. He found that for targets at shorter distances (3, 6 and 9 m) participants fell within 24 cm of the target location. However, as the distances increased, walking accuracy decreased such that there were systematic underestimations of the target distance. He concluded that prior vision could guide non-visual locomotion over an extensive range of distances. This aspect of his work has been replicated by several researchers (Elliot, 1986; Steenhuis and Goodale, 1988; Loomis et al. 1992; Rieser et al. 1990; Glasauer et al. 1994) and this methodology is still widely used to examine the contributions of prior visual input on non-visual locomotion.

Linear trajectories are not the only type of path that has been used to examine non-visual navigation ability. Viaud-Delmon et al. (1997) examined the accuracy with which normal and labrynthine-defective individuals could walk a previously seen triangular path without vision. She found that both groups were able to complete the task with some accuracy, although the patients showed larger directional errors when walking the corners of the triangle. Takei et al. (1997) reported that blindfolded participants were very precise at walking around different sized floor-drawn circles that they had previously walked around with vision; the distance around, the trajectory and turning angles of the circles were reproduced with little error. Comparing the navigation performance of early and late blind and blindfolded sighted individuals provides support for the importance of prior visual experience because late-blind individuals, who have had some early visual experience, perform as well as blindfolded sighted people on many tasks (Rieser et al. 1986; Loomis et al. 1993). However, reports of differences in the performance of early and late-blind individuals are mixed (Thinus-Blanc and Gaunet, 1997).

In assessing the contributions of visual information to navigation, it is necessary to mention the importance of optic flow. Under normal, everyday conditions, navigation can be accomplished by evaluating visual information about the environment, such as the locations of stationary landmarks at crucial decision points along a route. However, we also need information that tells us about our own movements in the world and this information can come from optic flow (Gibson, 1977). When vision is available for navigation, information from optic flow serves as a primary input to the path integration signal. In addition, the extensive visual-vestibular interactions, both anatomical and functional, also suggest that optic flow make a contribution to navigation. Velocity information that is derived from optic flow is used extensively by honeybees for navigation and flight control (Srinivasan and Zhang, 1997; Srinivasan et al. 1996) and can also be used by rodents and humans to guide navigation when visual cues are available (Gallistel, 1990). Due to the nature of the experiments in the present research, information from optic flow is absent and therefore participants cannot make use of this kind of information to solve the presented navigational tasks.

Non-Visual Contributions to Non-Visual Navigation

In his studies of the role of the vestibular organs in space orientation and non-visual locomotion, Worchel (1951, 1952) was among the first to empirically investigate the potential contributions of non-visual information (i.e. vestibular, somatosensory and motor efference copy) to navigation. Similarly, Beritoff (1965) conducted both human and animal experiments that implicated the vestibular system in spatial orientation and navigation. Beritoff (1965) reported that if a dog was blindfolded and *passively* guided (i.e. transported) to a food source, it could return to the food source without difficulty. Because olfactory, visual and motor efference information about the traveled path was eliminated through passive transport, the author was able to claim that the vestibular receptors played an exclusive role in the animal's behaviour. These claims were further supported by results of experiments with labyrinthectomized animals. These animals showed orientation disturbances even with the aid of vision and were not able to return to a food source which they had previously visited (Beritoff, 1953 as cited in Beritoff, 1965). This effect was also seen in people with nonfunctioning labyrinths. When children with no vestibular perception were blindfolded and repeatedly led along a route to a goal they showed difficulty in retracing this path (Beritoff and Kherkheulidze, 1958a, as cited in Beritoff, 1965).

Potegal (1982) proposed the *vestibular-navigation guidance hypothesis*, which he defined as dead reckoning based on vestibular input. In discussing evidence for his hypothesis, he noted that the vestibular system was the most appropriate physiological system for navigation for several reasons. It is a sensitive and reliable system, its signals are integrated by the CNS at various levels and it has connections to other CNS structures that might be involved in the computation of navigational vectors (also see Wiener and Berthoz, 1993). As behavioural evidence for his hypothesis, Potegal (1982) cited a) Beritoff's (1965) early clinical studies mentioned above, b) studies in passive human transport where the perception of distance and velocity are tested when all but vestibular input is controlled and c) the few early studies of human non-visual locomotion. He also noted animal experiments that examined the effects of active and passive locomotion on homing as well as studies that assessed the effects of vestibular damage on navigation and path integration. For example, Miller et al., (1983) investigated the contributions of the vestibular system to spatial orientation in the rat by assessing the ability of enucleated rats and rats with either vestibular nucleus or cerebellar cortical lesions to return to a waterspout location after passive transport to and from its location. Results indicated that rats successfully learned to return to the waterspout after passive transport and could relearn the task after enucleation but not after vestibular nucleus or cerebellar lesions. Their results suggest that, for passive transport tasks, removing vision while maintaining an intact vestibular system does not affect the ability to return to a previously visited place but destruction of the vestibular system does affect navigation ability. This result is compatible with what Beritoff (1965) reported and also supports Potegal's hypothesis.

More recently, research interests have focused on the influence of non-visual sensory information (generated by locomotion) on human place navigation, distance and direction estimation and path integration. Place navigation (Sutherland and Dyck, 1984) has been defined as the ability to find the way back to a place that has been previously visited. In the absence of vision, path integration is the process thought to underlie place navigation. The current experimental protocol used to investigate human place navigational ability in the absence of vision requires that either a blind or a blindfolded sighted individual be guided along a path or be passively transported for a specified distance and direction from a known point of departure (Ivanenko, 1997; Berthoz et al. 1995; Klatzky et al. 1990). Following this, participants are instructed to complete a variety of tasks, usually motoric in nature, which examines their ability to utilize the sensory information acquired from locomotion to replicate or estimate the traveled path. The task that was used in the present work requires participants to return to the location to which they were led, thus requiring them to replicate the direction and distance of the traveled path.

Few studies have assessed the accuracy of non-visual navigation and other spatial behaviours that make use of sensory <u>input</u> from non-visual locomotion. This is different from assessing non-visual navigation based on prior visual input. Klatzky et al. (1990, 1995) examined non-visual distance reproduction and estimation after individuals without vision walked a straight line guided by a rope. The researchers were interested in how well individuals could maintain heading and reproduce a path they had learned without vision when no visual feedback was allowed during reproduction. It was found that general heading could be reproduced but that there was evidence of veering during the non-visual walk. However, despite the veering, distances were accurately reproduced. In a second experiment, participants were guided along more complex paths without vision and were asked to return to the origin of their travel. It was found that as the number of path segments increased, return-heading error increased but that it was the complexity of the path (i.e. the turn angles) rather than the absolute number of path segments that affected performance the most. Parts of Klatzky et al.'s (1990) study were replicated by Loomis, et al. (1993) who compared the ability of blind and blindfolded sighted individuals to estimate and reproduce walked distances that were previously traveled without vision. They showed that both groups were able to accomplish this kind of simple locomotion task adequately but there were systematic errors in the performance of both groups; as distance increased, reproduced distances fell short of target distances. Loomis et al. (1993) also studied more complex spatial behaviours like turn estimation, turn reproduction and triangle completion, a task that if completed accurately implies that path integration is at work. For the more complex tasks like turn reproduction, there appeared to be a tendency to underestimate large angles and for the triangle completion task, participants were said to be, on average, "...sensitive to the manipulations of length and turn angle." (p. 83, Loomis et al. 1993). However, the performance data suggest that the triangle completion task was difficult and the non-visual information supplied by locomotion was inadequate for path integration. Passini, Proulx and Rainville (1990) examined the spatio-cognitive performance of early and late blind and blindfolded sighted individuals on a number of different elements of a locomotor wayfinding task that used a life size experimental maze. One part of the task required participants to learn and reproduce routes through the maze that had either 3 or 5 decision points. A second task required them to invert the previously learned route by walking from the destination point to the origin and the third task asked participants to indicate, by pointing with their arm, the direction of the origin from a point within the maze. Regardless of their visually impaired status, all participants were able to perform these tasks but the accuracy of their performance was frequently related to their degree of visual impairment. Incidentally, there were some tasks on which the congenitally blind performed better than blindfolded sighted people. One reason for this may be that the blind have experience with non-visual locomotion as they engage in wayfinding daily. Although studies of navigation in the blind contribute to our understanding of how the non-visual senses impact on the ability to determine distance, direction and the relations between objects, a blind person is not exactly like a blindfolded sighted person. Lack of early visual experience has been shown to lead to differences in brain organization (Neville, 1995) which may be one reason for the performance differences in blind and blindfolded sighted individuals. In her landmark study, Landau (1981) and her colleagues (Landau et al. 1984) investigated the use of metric knowledge and navigation ability in Kelli, a very young blind child. Kelli was taught the spatial arrangement of four objects in a room by being led to each object from a starting point, which was one of the four objects. For instance, she learned the space by being guided away from her mother, who was sitting on a chair (M), to a stack of pillows (P) and back. Subsequently she was guided from M to a table (T) and back and was then walked from M to a basket of toys (B) and back. She was allowed to haptically inspect the objects at each location. In order to test her spatial knowledge, she was asked to walk from one object to another along a route she had not walked before. Their experiment showed that Kelli was able to geometrically represent space in such a way that enabled her to set a course between objects along a route she had not previously walked (e.g. from B to P). In order to accomplish this, the child must have had access to information about the distances and angles between the objects in order to derive the novel routes that linked the objects. Although the results were discussed in terms of whether the metric properties of space can be appreciated by the very young, it was clear that the non-visual sensory information Kelli acquired by walking to and from the objects' locations was instrumental in helping her develop this geometric representation of space.

These studies and others have provided valuable insights into the understanding of human non-visual navigation but few studies have looked at whether blindfolded sighted individuals are able to return to a location in space after learning that location without vision. If non-visual sensory information is supposed to be used for navigation, it would be useful to know whether an individual can learn the location of a goal by utilizing only non-visual information in order to return to that location later. This type of task, which would examine whether individuals could use non-visual information to encode the distance and direction to a goal also asks whether people can use path integration to solve simple spatial tasks. Experiments 1, 2 and 3 of this thesis examine the contributions made by non-visual sensory information to performance on tasks of place navigation, distance and heading (direction) estimation.

Sex Differences in Spatial Abilities

Differences in spatial ability between males and females are very well established in both the human (e.g. McGee, 1979; Linn and Petersen, 1985; Voyer, Voyer and Bryden, 1995) and animal literature (e.g. Williams, Barnett and Meck, 1990; Einon, 1980; Juraska, Henderson and Müller, 1984). Although many hypotheses have been offered to explain these differences (e.g development/socialization; heritability; hormonal influences; hemispheric specialization) (Newcombe, 1982), there is no consensus on what might best explain their nature.

The magnitude of sex differences in spatial ability is not always agreed upon but the direction of sex differences is undisputed; robust and persistent sex differences favoring males have been reported for tasks that require spatial visualization, mental manipulation of spatial designs and spatial orientation (e.g. McGee, 1979). Similarly, Galea and Kimura (1993) have found that males are better than females at remembering directions of a route learned from a map and are better able to visualize their orientation at different points along the route.

To a large extent, the data documenting sex differences in human spatial ability come from the assessment of skills that are cognitive or perceptual in nature (Linn and Petersen, 1985; Newcombe, 1982). That is, abilities for which sex differences are found are those that deal with manipulating and constructing objects or designs, visualizing objects in multiple orientations and dimensions, and memory for map features, routes, landmarks and other geographical information. In contrast, because research with animals precludes assessing these types of skills, the study of animal spatial ability has focussed on how well they can remember the location of a food source, a hidden platform or which arm of a radial maze they have previously visited (Olton, 1982). By assessing the spatial performance of animals using these kinds of tasks, we might learn about what information they encode by locomoting within their environment and how they can utilize this information in order to represent distance, direction or to solve navigational tasks. We have defined these skills as spatial performance skills and it is these kinds of abilities that represent an important part of spatial behaviour in humans because they assess how we might act or perform in the real world. Based on the data that support male's superior performance on cognitive-perceptual spatial tasks, we might be led to conclude that the same pattern of differences would also be seen on tasks that assess spatial performance. However, to date, the literature on human spatial abilities have not addressed sex differences in spatial performance, perhaps because there are no differences or they are not interesting. The experiments of this thesis fill this gap by explicitly examining gender differences on spatial tasks that require performance in the real world.

The Importance of the Nature of the Response Output in the Study of Navigation

A comment must be made on two issues that are not formally addressed in the literature on human navigation. The first issue is related to the nature of response output that measures an individual's navigation performance or spatial knowledge. Examples of response outputs commonly found in the literature are locomotion, pointing, map drawing and verbal responses. Because each response output is motorically different, the way in which space is represented by each response system is also potentially different. Thus, each response output might generate a different measure of the spatial behaviour being studied. This will subsequently impact on the interpretation of results. For example, when you draw the corridors of a maze that you have walked through, their lengths may be different than your verbal estimations of their lengths even after the size of the drawing has been taken into account. This is because in order to draw your representation of locomotive-experienced space, such a representation must be transformed to fit into an entirely different space – the paper.

If response output is important, which type of response is the most appropriate for the study of human navigation? Because pointing and locomotion are the two most common response outputs used, they will be discussed to illustrate the point. Pointing is an appealing response output because it is easy for participants to produce, it is simple enough for experimenters to score and it is a motor output. However, the pointing response is limited in what it might tell us about the representation of space; it does not provide distance or positional information and only really indicates knowledge of general heading. Pointing may also have limited value when attempting to understand how space is represented during locomotion. This is potentially crucial in the study of navigation, as navigation requires locomotion. Based on this fact alone, it should be evident that locomotion is the most appropriate response output to use in the study of navigation because it does not differ from how navigation is accomplished in the real world. A locomotive response provides data on an individual's knowledge of the heading of their journey, their orientation during the journey and the distance of the target to which they were led. A locomotive response output can also be used to study the extent to which spatial information was encoded and processed as evidenced by shortcuts. Pointing does have its place however; it may be the most parsimonious response when heading is all that is of interest and it is practical in the sense that one may obtain data about how an individual is able to indicate multiple locations in space.

The second issue that bears on the way spatial navigation ability is measured is related to the first and is based on the way in which spatial information is acquired. It has been found that there are differences in the type of spatial knowledge that is acquired from studying maps than from actually navigating within the environment (Thorndyke and Hayes-Roth, 1982). The type of spatial knowledge acquired has an impact on, for instance, the ability to indicate the directions of and distances to different locations within that environment. When studying a map, space is typically represented using the perspective or orientation of the viewer. If the viewer were asked to indicate a given location from another position or orientation, their judgments may be affected because their memory for information learned from the map is orientation specific (Evans and Pezdec, 1980; Presson and Hazelrigg, 1984; Thorndyke and Hayes-Roth, 1982). However, if space is represented through an active exploration of the environment, first hand knowledge of the spatial relations between locations is acquired (Thorndyke and Hayes-Roth, 1982). Individuals who learn a route through locomotion may be able to indicate the locations of objects or important route junctions from a unique orientation or novel position with more accuracy than had they learned the route from a map. As a result, exploring the environment leads to more flexible navigation ability because of the way spatial relations are represented (Presson and Hazelrigg, 1984, 1989). The point here is that, if one wants to study and understand the mechanisms underlying navigation, it might be best to study it using the most appropriate response output: Locomotion.

Combined Visual and Non-Visual Sensory Information on Non-Visual Navigation

There are no studies of human navigation that explicitly compare the effects of combined visual and non-visual sensory input on non-visual navigation performance. In an attempt to understand what types of cues animals use to solve simple spatial navigation problems, researchers have manipulated the availability and congruence of visual and non-visual cues. In the presence of distal (room) and local (within the arena) cues, either may be used to solve a spatial navigation task when vision is available. But, in the absence of external references (i.e. visual cues), animals may rely entirely on self-generated signals that arise from locomotion. Etienne and his colleagues (1993) investigated the control exerted by conflicting spatial cues on short distance navigation in the golden hamster. Animals were trained and tested in the same circular arena where both distal and sometimes local cues were available. After hoarding from a food source that was located at the center of the arena, hamsters returned directly to their nest that was located at the periphery of the arena. During training trials, visual cues were correlated with non-visual or dead reckoning cues so that the animal learned to associate the nest entrance with this information. However, during experimental trials, the cues were set into conflict and the location to which the animal returned after hoarding was observed. When the arena was rotated 90 ° before the animal left the nest, the animal first used distant visual cues to return to the original location of its nest. But because the nest had shifted 90 ° this return location was incorrect. Eventually, the majority of the animals learned to recalibrate the role of non-visual information after many trials and returned to within 10 ° of the rotated nest. Teroni, Portenier and Etienne (1987) found evidence for the influence of non-visual cues on animals' performance, when they studied spatial orientation and navigation in hamsters that were subjected to conflicting location and route-based spatial information. Even though the hamsters' responses were obviously guided by visual cues, there was a subtle effect of non-visual information on their performance. The same subtle effects of non-visual information were observed by Etienne and his colleagues (1993) as the mean return heading of some of their animals on the first test trial was biased slightly towards the location of the rotated nest. These findings illustrate the potential role of non-visual information in navigation tasks even when vision is available.

For people, receiving both visual and non-visual information about the location of a target may lead to a number of possible performance outcomes. For instance, it may be the case that both visual and non-visual information are mutually exclusive, that is, they provide two unique estimates of a targets' location in space. If these two pieces of information estimate a target's location accurately and both types of information are used in the estimating its location, then combining the two types of information should result in relatively accurate performance. Indeed, combining two unique and equally accurate estimates of target location might even make performance more accurate than having visual or non-visual information alone. On the other hand, even if visual and non-visual information provide two unique estimates of target location, the information acquired from viewing the target's location might override that which is provided by non-visual information.

Alternatively, perhaps the information from the two different modalities is averaged without regard for whether visual or non-visual input produces a more accurate estimate of the parameter in question. In this instance, an individual that has learned the location of a target both visually and non-visually will generate an intermediate response, not perfectly accurate but not obviously inaccurate. However, the extent to which information from either visual or non-visual input leads to an under- or overestimation of the distance or heading of the target, combining the two kinds of information would result in less than accurate performance. Collett and Harkness (1982) point out that frogs combine depth cues from both stereopsis and accommodation systems in order to estimate distance. The combination of both depth cues occur despite the fact that stereopsis, when vision is binocular, provides a far more accurate estimate of distance than accommodation. It becomes important to ask whether there are advantages to using both pieces of sensory information, especially when one sense might not contribute as much, or could adversely affect the estimate of the parameter in question. In other words, for the frog, how much more information about distance can accommodation provide to the overall estimate? Collett and Harkness (1982) reported that if the two cues are pitted against one another experimentally, the frog's distance estimate could be predicted by summing a weighted depth estimate provided by accommodation and a weighted depth estimate provided by stereopsis. The specific weight or value attached to each depth estimate is based on the accuracy with which that sense can estimate depth and use it as a cue for distance. These authors also noted that it is not always optimal to choose one cue over the other as one piece of sensory information can serve as a backup when information from the other cue is lost or not available.

Although people, like animals, may rely solely on prior visual input (should it be available) to guide their non-visual locomotion, non-visual information will exert some influence on their performance. However, because non-visual information likely does not provide as precise an estimate of target distance and direction as does vision, they may perform less accurately than someone who had received vision alone. This seems to be the most likely outcome in a situation where a blindfolded individual attempts to return to a location they had previously viewed and also learned without vision. The combined influence of visual and non-visual information was examined in Experiment one.

Purpose

The present research examined the relative contributions made by visual and non-visual information to non-visual place navigation performance, path integration ability, distance and heading estimation. Also, because there are few studies that examine gender differences on spatial tasks that require locomotion, the experiments in this thesis fill this gap by assessing the performance of both genders on locomotive performance tasks.

EXPERIMENT 1

To examine the relative contributions of visual and non-visual sensory information to place navigation performance, experiment 1 assessed the accuracy with which a blindfolded individual could return to a single location in space that was previously learned either visually, non-visually or with combined visual and non-visual input. Instead of having people return to the point of origin after travel, which is a common way to examine path integration ability, participants were required to return to the place that they had previously visited. By asking participants to reproduce their traveled path to the target location, their ability to encode and store information about the distance and direction of travel from non-visual sensory input could be observed. Although other studies have indicated that this type of task may be accurately accomplished without vision, our task was different because participants were guided without vision to and from the target location before responding.

METHOD

Participants

Forty-eight healthy right-handed undergraduates (24 women and 24 men) from the Department of Psychology at the University of Waterloo participated in the study. Participation was voluntary but students involved received course credit.

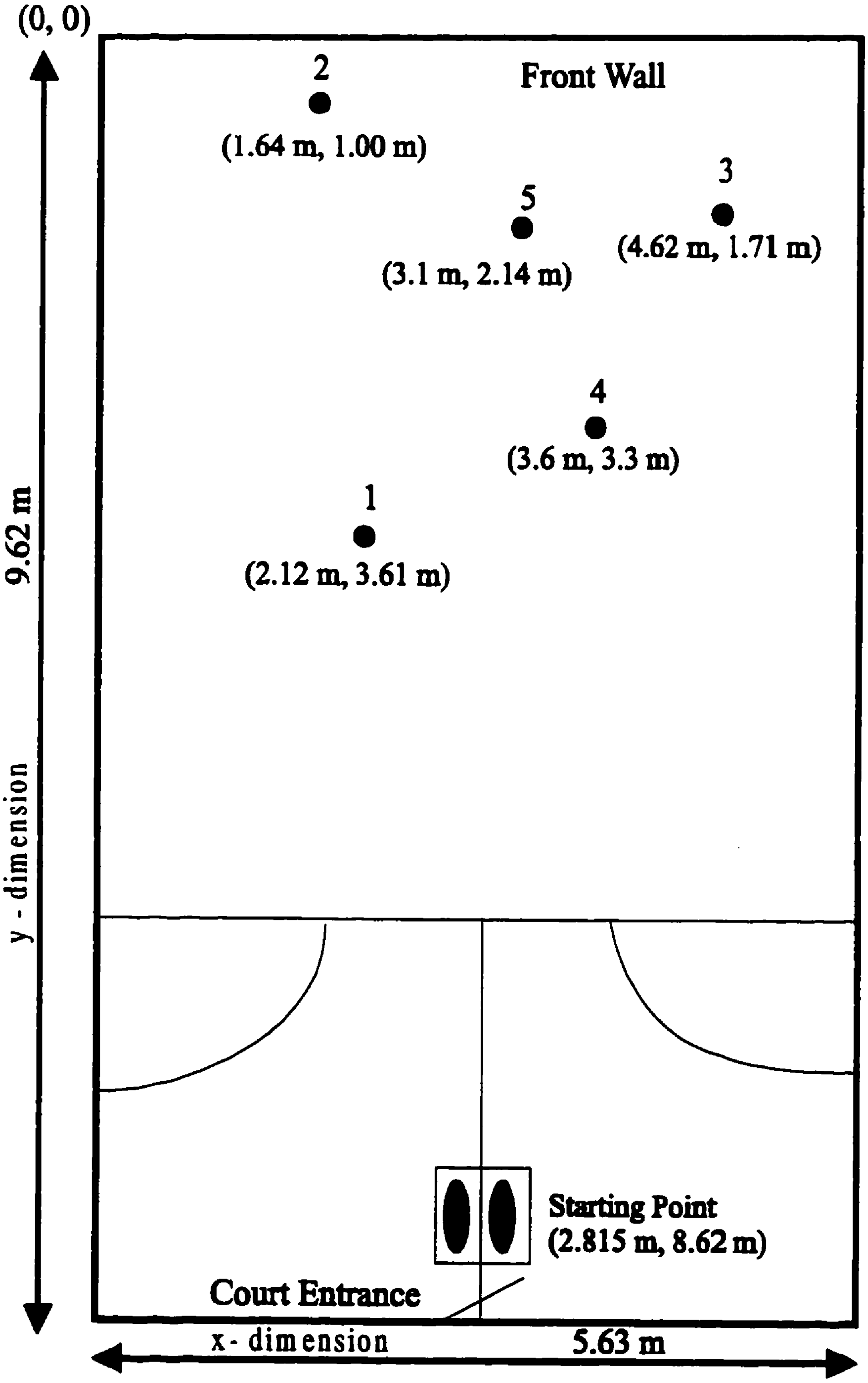
Apparatus and Materials

All experimental trials were conducted within the confines of an indoor squash court at the University of Waterloo's Physical Activities Complex. The court dimensions were 5.63 m x 9.62 m but only the fore half of the court (5.63 m x 3.63 m) was used for the target locations. A set of raised foot impressions (30 cm x 35 cm) were placed one meter from the court entrance and served as the location of the starting point for each navigation trial. Figure 1 illustrates the layout of the target locations. All targets were placed in the fore half of the court and ranged from 5.31 m to 8.12 m from the starting point in the y-dimension. The eccentricity of targets ranged from 2 ° - 15 ° and straight-ahead was measured as 0 °. A black circular disc 10 cm in diameter was used to identify the target locations in the trials where vision was available. All trials were recorded by a video camera that was positioned in the viewing gallery above the court. To calibrate the workspace, a grid composed of squares (each 1 m^2 except at the ends of the grid) was laid onto the floor of the court and videotaped prior to each testing session. The grid was not present during experimental trials. The videotaped grid images and all responses were captured by a commercially available frame-grabbing interface (ATI All-In-Wonder video card and ATI Player) and saved on computer. Cartesian coordinates of pixel locations in the graphics images were converted to physical locations using transformations derived from the grid of each experimental session.

Procedure

There were two parts to the experiment; information acquisition and response. Participants were randomly assigned to one of the following information acquisition groups: a) the vision group b) the non-vision group or c) the both group. Prior to the experimental trials, participants received practice walking blindfolded with and without being led by the experimenter. Darkened goggles and protective earphones were worn to eliminate the use of visual and mute auditory information, respectively. In order to learn the

Figure 1. (Experiment 1). Scaled bird's-eye view of the squash court dimensions, the location of the starting position and the location of each target location.



locations of the targets without vision, participants held onto a cardboard tube as if it were a water-ski bar and the experimenter guided them to and from each target location by gently pulling on the rope that was attached to the tube's center. Other than verbal warnings that were given to a few individuals to avoid collisions with walls, no feedback was given during the experiment. All responses were made without vision.

Information Acquisition

Participants in the vision group first viewed a target location (indicated by the disk on the floor) from the starting point. In order to equate this group with the other groups that received non-visual information about the target's location, participants turned away from the court for approximately 25 seconds (the time required to be led to and from any given target location). After this short period, participants were given a few more seconds to view the target and then walked, blindfolded and unaided, to the place where they remembered the target to have been. Upon completing the response participants were led back to the starting position. Participants in the non-vision group were blindfolded and guided from the starting position to a target location, turned around on the spot and led and back. Upon returning to the starting position they remained blindfolded, were reoriented forward and were asked to walk back to where they were just guided. After their response, participants remained blindfolded and were led back to the starting position. To prevent counting footsteps during the outbound and return legs of the journey, participants were asked to recite the sentence, "White bears, red foxes and green frogs make very good friends". Those participants in the both group first viewed a target location from the starting point and were then blindfolded and led to the target location and back. Once at the starting position again, the participants were allowed to briefly view the target location before walking to where they remembered the target to have been. Upon completing the response they were led back to the starting position.

Data Analyses

Responses were measured midway between participant's feet at the terminal point of locomotion. All responses, the target location for the vision and both conditions and the location to which each participant was led were extracted from videotape. Responses from the vision group were compared to the target locations indicated by the black disk. Because it was very difficult to lead participants to the precise location of the disk, the responses of participants from the non-vision group were compared to the location they were walked to rather than the location of the black disk. For example, some people took larger natural steps, some walked slowly and some had more upper body sway or arm swing than did others. On average, however, walked locations were within approximately 8 - 10 cm of the target's actual location. Responses from participants in the both group were compared to an average of the real target location and walked location.

An inherent limitation of using video images is that in converting video data to real life coordinates there is a loss of spatial resolution. The scaling of the image from the camera was transformed by the application of best-fit polynomial equations. As a result of converting the video image of the workspace, which itself was in perspective[1], to a 2-D pictorial representation, the mathematical transformations used to convert pixel

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[1] The video image depicts the Y-axes progressively converging, and the x-axes becoming progressively shorter as one moved from the bottom to the top of the image. This was mainly due to the location of the video camera during filming (high off the ground but not directly overhead), the distance of the testing area from the camera and also the properties of the lens on the video camera.

information to meters were inexact. Although the converted data points do not perfectly match to real world locations, the conversion from pixels to meters was accurate to within 5 – 10 cm.

RESULTS

All analyses in this thesis were evaluated at an alpha level of .05. In instances where the univariate repeated measures ANOVA assumption of sphericity was violated, the Greenhouse-Geisser's Epsilon correction factor was used to adjust the degrees of freedom (Howell, 1992). F-ratios were reevaluated using the corrected degrees of freedom and only the adjusted degrees of freedom are reported. The Greenhouse-Geisser's Epsilon correction factor is appropriate to use for severe violations of sphericity because it is less conservative than the Lower Bound Epsilon but more conservative than the Huynh-Feldt correction factor (Cohen, 1996). If the observed F-ratio is larger than the conservatively corrected critical F, then that F-ratio is validly significant regardless of the degree of sphericity violation.

Performance error was examined in the following ways: <u>Heading error</u> in degrees was the ideal heading minus the response heading and <u>distance error</u> in meters was the ideal distance minus the response distance. Heading here is defined as the final direction (as measured from the straight-ahead position at the origin) of the participant's locomotion after they have stopped walking. Distance is defined as the total distance walked. Table 1 shows the means and standard errors for all unsigned and signed errors.

<u>Unsigned Heading Errors</u>

Unsigned (absolute) heading error does not take into consideration whether a given response falls to the left or to the right of the target location but it is a good general measure of heading error (Klatzky et al., 1990). A repeated measures ANOVA on group, gender and target location showed a significant effect of group <u>F</u> (2, 42) =

27.21, $p < .001$. Post-hoc, Fisher's least significant difference (LSD) test revealed that the unsigned heading error for the non-vision group was significantly greater than the heading errors of the vision group ($p < .001$) and the both group ($p < .001$), which did not differ from each other (Figure 2a).

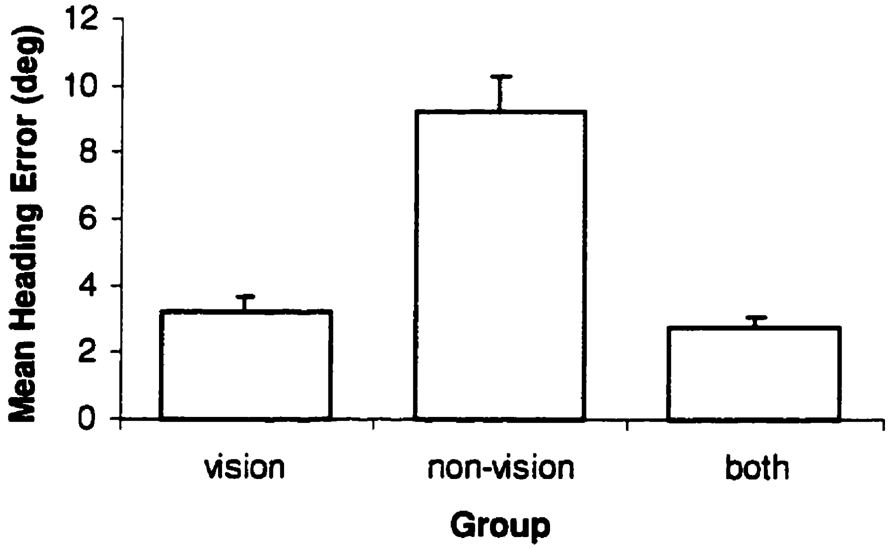
Unsigned Distance Errors

Unsigned distance error does not take into consideration under- or over-shoots of the target location but it is a good measure of the distanced traveled. A repeated measures ANOVA showed only a significant effect of group F (2, 42) = 7.34, $p < .005$; the mean unsigned distance error for the non-vision group was significantly greater than the mean error of the vision group, (LSD: $p < .005$) and the both group, (LSD: $p < .005$). The vision and both groups did not significantly differ from each other (see Fig. 2b).

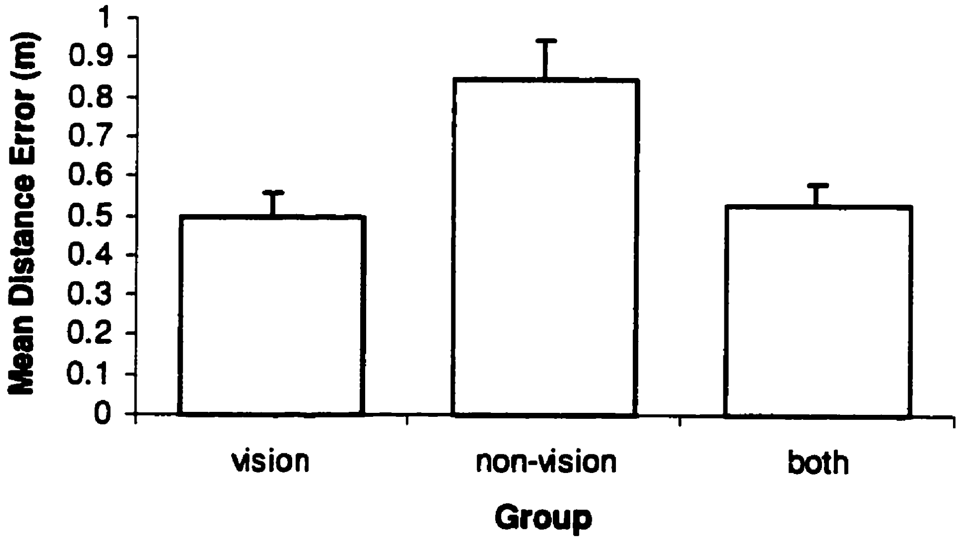
There was a significant effect of target location (TL), F (4, 168) = 3.31, $p < .05$, but no interactions. The distance error for TL 2 was the lowest and was significantly lower than distance errors for TL 3 (paired t [47] = -2.98, $p < .01$) and TL 5 (paired t [47] = -2.97, $p < .01$), which had the largest error (see Table 2). Because of the location of TL 2, a few individuals in the vision and both groups tried to use the front wall to aid their localization of the target by walking to the wall, touching it and then taking a few steps backwards. Independent t-tests revealed that using the wall to localize TL 2 was not advantageous and there were no significant differences in distance error between individuals who used the front wall and those who did not.

Figure 2. (Experiment 1). **A**. Mean of unsigned heading errors in degrees for each group. **B**. Mean unsigned distance errors in meters for each group. Responses were summed across target locations. Error bars are standard errors.

A



B



Signed Heading Errors

Signed heading error is a useful measure because it indicates whether a response was made to the left or to the right of the actual target location. Based on the calculations, a positive heading error places the response to the *right* of the target location and a negative heading error places the response to the *left* of the target location. A repeated measures ANOVA showed a significant effect of gender F (1, 42) = 7.69, $p < .01$ which was qualified by a significant interaction between group and gender F (2, 42) = 4.09, $p < .01$ shown in Figure 3. Specifically, males and females in the non-vision group differed significantly in their overall heading as males veered to the left considerably while females veered slightly to the right. There was an effect of target location, F (3, 118) = 3.03, $p < .05$ but it also interacted with group, F (7, 118) = 2.51, $p < .05$. This suggested that, depending on the type of sensory input received, the headings of some target locations were more difficult to reproduce. Further analysis showed that TL 3 produced the largest heading error overall, F (2, 45) = 5.37, $p < .05$ and for this target location, the non-vision group produced significantly more heading error than the vision ($p < .005$) and the both groups ($p < .05$).

Signed Distance Errors

Signed distance error is useful for distinguishing responses that are under- or over-shoots of the target location. A *negative* distance error indicates an undershoot of the target while a *positive* distance error indicates an overshoot. A repeated measures ANOVA showed a significant effect of group F (2, 42) = 5.89, $p < .01$. Examination of this main effect revealed that the distance error produced by the both group was found

Figure 3. (Experiment 1). Group by gender interaction for signed heading errors. A negative value represents a response to the left of the target (left veer) and a positive value represents a response to the right of the target (right veer). Error bars indicate standard errors.

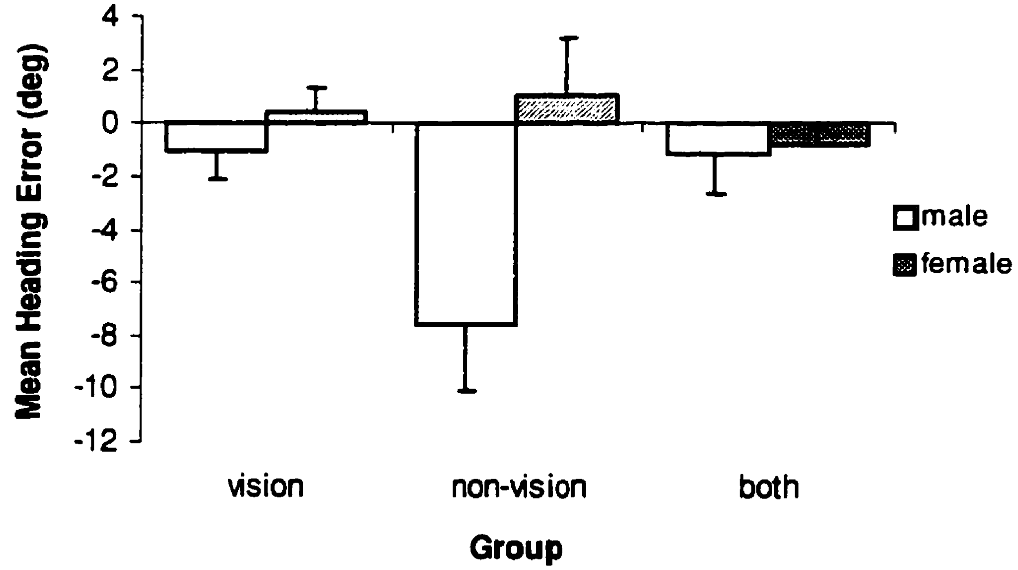
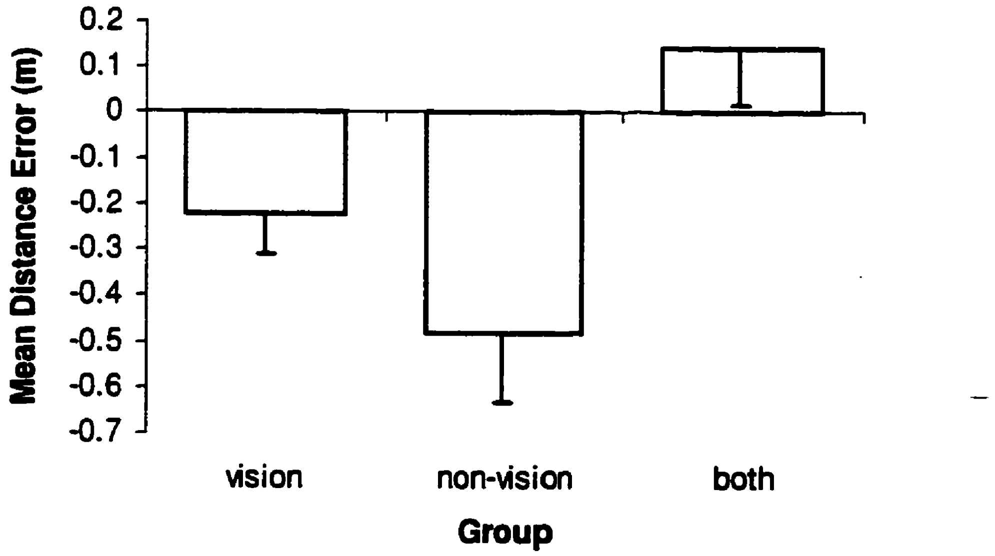


Figure 4. (Experiment 1). Mean signed distance errors in meters for each group. Responses were summed across target locations. A negative value represents an under-estimation of the target while a positive value represents an overestimation of the target. Error bars are standard error of the mean.



to be significantly different from the vision and the non-vision groups (LSD: $p < .05$ and $p < .005$, respectively), which did not differ from each other (Figure 4). The both group overshot the target distance slightly while the other two groups under-estimated its distance (refer to Table 1).

Distance and Heading Error: Was Performance Better than Chance?

There was a concern that participants in the non-vision group were performing at chance levels. Theoretically, the average response when individuals have no information about target location falls dead ahead in the center of the court from the starting position. Using this theoretical response location we computed both a chance heading and a chance distance response. If participants behaved randomly or if no information about target location was provided, their average response across all target locations would fall in the center of the court and there would be no significant difference in error when one compared the participant's response and the chance response. However, if participants walked with some accuracy towards the target locations, their distance and heading errors would be different from the random response. One sample t-tests revealed that, for distance, the mean response error was better than chance, $t\ (15) = -1.73$, $p < .001$, but for heading, the overall performance was no better than chance $t\ (15) = .74$, $p > .1$. Participants in the non-vision group were more accurate at replicating distance than heading for target locations in the present study.

DISCUSSION

The goal of this experiment was to examine the potential contribution of non-visual sensory information to place navigation accuracy and path integration ability. We approached this problem by employing a method that was unique in terms of how the spatial information about a particular target location was acquired. Specifically, participants in the present experiment were led without vision to and from each target location before they were then asked to return to that location without vision. Loomis et al. (1993), Klatzky et al. (1990) and Rieser et al. (1990) have all studied non-visual navigation ability in blind and blindfolded sighted individuals through non-visual locomotion but the methods by which individuals acquired non-visual information were not the same as that which was employed here. Loomis et al. (1993) for example, led blindfolded participants to a location in space and then asked them to reproduce, without vision, the distance they had traveled from the point at which their guided walk was terminated. Klatzky et al. (1990) studied the same skill but instead of asking individuals to respond from the point at which their non-visual guided walk ended, participants were repositioned within the workspace before they were asked to reproduce the distance and heading they had traveled without vision. The underlying goal of the present experiment, which inspired the method, was to examine non-visual navigation in a manner that was as close to a real world task as possible. This was accomplished by making the target locations serve a purpose; participants had to remember their locations because they would be asked to return to them. The method allowed us to draw conclusions about place navigation and path integration ability as well as assess the accuracy with which distance and heading could be encoded and reproduced. By comparing the performance of participants in this non-visual condition to conditions in which the same target location was learned with vision alone or with a combination of visual and non-visual information, we were able to assess the relative contribution of non-visual information to these kinds of skills.

The Effects of Non-Visual Sensory Input on Non-Visual Navigation Performance

When absolute values of errors were considered, participants that received only non-visual information (non-vision group) about target location were significantly less accurate both at reproducing the heading towards and the distance to the location to which they had been led previously. Although there was a lot of variability in performance[2] (see Figure 5), our findings suggest that overall, people have considerable difficulty finding their way back to a location a short distance away when they have not seen the target. The magnitude of distance and heading errors produced by participants in the non-visual group also indicated that relying on non-visual sensory input alone to learn a location in space is not sufficient for subsequent non-visual navigation to that target. Loomis et al. (1993) conducted a similar experiment with blind and blindfolded sighted individuals. He led participants on a straight route for 2, 4, 6, 8, 10 or 12 m and then asked them to reproduce this distance by walking forward from the point where the

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[2] Although idiosyncratic differences in navigation ability may be a plausible explanation for the large variability in responses of participants in the non-vision group, the method by which participants were led to the target location may also have produced this effect. Based on the procedures employed by other researchers (e.g., Loomis et al. 1993), we tested twelve additional participants in the non-vision condition by leading them two different ways. In alternative method one, six participants guided themselves to and from each of the five target locations by following a rope and in method two, six different participants were led to the target location by holding onto the arm of the experimenter (traditional method for guiding the blind). The participants from this group walked at their own pace but were led by the experimenter to and from the five target locations. Results indicated that performance accuracy did not increase as a result of changing guiding methods. Both the rope and arm guiding methods resulted in

guided walk ended. Although heading was not examined, the errors produced by his participants at distances greater than 4 m were comparable, if not larger, than errors made by participants in the non-vision group of the present experiment. Interestingly, Loomis et al. reported that his participants performed the task relatively well.

Based on the concept of path integration, we made the assumption that non-visual information would generate estimates of position, distance and direction that were independent of, but similar to, estimates based on visual information (but likely with somewhat poorer spatial resolution). On the basis of this we hypothesized that the both group should perform more accurately than the vision group because these participants would be receiving two unique estimates of target location. This hypothesis was based on the fact that we assumed that both estimates would be equally precise and that performance would be enhanced. Unfortunately, we did not find this result. Instead, our data suggest that the information about target location that was provided by vision outweighed the potential contribution from non-visual input because vision provided more precise information about the target's location. However, we did find that this group, overall, overestimated the distance of the targets in comparison to the other two groups. Based on this response it may be concluded that even though non-visual information was less precise, it still had some effect on the response. Etienne et al. (1993) have shown that when hamsters are trained to return to their nest at the edge of a circular arena after obtaining food from its' center, their return heading is precise and they rely on distal visual cues. However, if the animal and arena are rotated prior to food acquisition, the animal's subsequent return heading to its nest is some sort of

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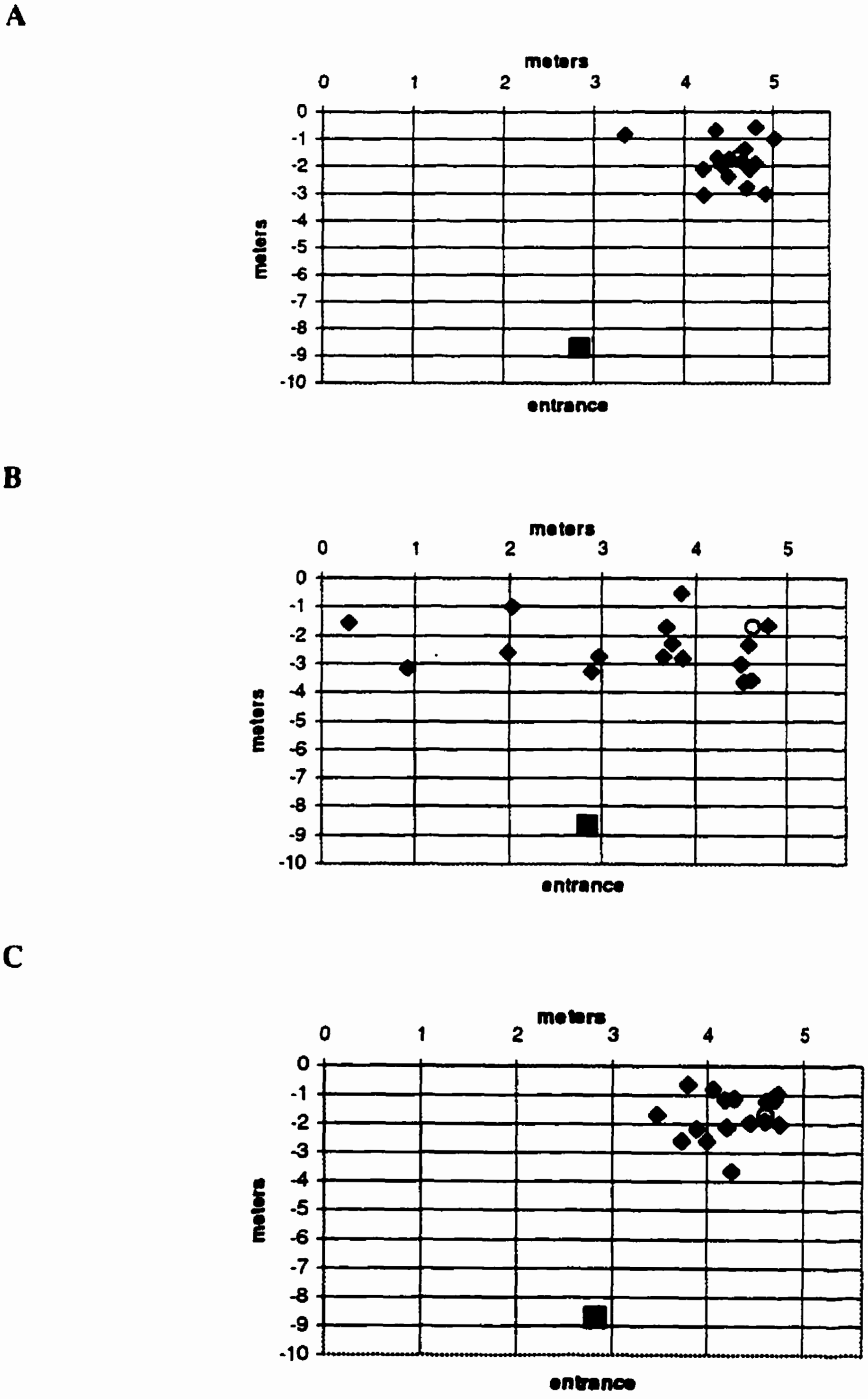
errors very similar in magnitude and direction to those produced by the method reported in this paper, suggesting that the variability seen in the performance of the non-vision group was natural.

average of the available visual cues and the non-visual, self-generated sensory information of it's outward journey

Figure 5. (Experiment 1). Scatter-plots illustrating participants' responses for target 3. Stippled circle represents the target, filled diamonds represent responses and the starting point is a square. **A**. Vision group. **B**. Non-vision group (note the variability in participant's responses) **C**. Both group.



to the food source. Etienne et al. (1993) described this behaviour as the result of the concomitant influence of non-visual sensory information on path integration and suggests that it is "always at work". Thus, it appears as though non-visual information alone cannot contribute to a direct estimate of target location but the information we get from non-visual locomotion somehow influences estimates based on visual information. Perhaps when visual information is available non-visual information can only influence the participants' perception of place if it conflicts with the visual information.

Target Underestimations

With the exception of the both group, there was a systematic underestimation of all target locations, the non-vision group producing larger underestimations than the vision group. One possible explanation for this finding may be that participants perceived they had walked farther than they actually had and stopped short so as not to overshoot the target. Walking without vision may have made participants walk at a slower pace so they felt more comfortable under such unusual circumstances. Consequently, participants may have inadvertently decreased the size and increased the number of steps they took which created the feeling that they had covered a large distance. Unfortunately, because of the experimental setup, we were unable to obtain the details of participants' step characteristics from the videotapes. Indeed, the majority of individuals not only stated that they felt they had walked farther than their response indicated, but when given practice walking blindfolded prior to testing, individuals walked half the court's length and then extend their arms as if they were about to touch the front wall. Glasauer et al. (1994) reported that some individuals used step length and some used step frequency to determine self-position from self-motion. Thus if step frequency and length changed during blindfolded walking in this experiment, distance estimation may have been misjudged.

The Effect of Target Location

As mentioned in the results, navigation to the farthest target (TL 2) was most accurate. We suspected that this finding was related to the proximity of TL 2 to the front wall; some participants who received prior vision of the target attempted to reach the target without vision by walking to the wall and taking a step backward. Sometimes this strategy worked against participants as they took too large a step or too many steps backward thereby underestimating the target. Concerned that this might be the case, we carried out further analyses which showed that there were no differences in distance error between those few that employed this "wall-tactic" and those who simply walked to the target and therefore could not entirely account for the accurate navigation to this target. In contrast, navigation to the next two farthest targets (TL 3 and TL 5) was similarly as inaccurate. No strategy could be used to reach TL 5 because of its location in the center of the court but TL 3 was close enough to the right wall that a strategy similar to that used to reach target 2 could have been employed. However, this did not occur. Despite the proximity of some of the targets to the walls of the court, three factors make us confident that our results were not influenced by participants' fears about colliding with a wall. First, participants were given an opportunity to explore the court boundaries, second, participants experienced walking without vision prior to testing and finally, the experimenter carefully monitored participants' positions during each trial.

Sex Differences in Heading Bias

Few studies report gender effects for these types of spatial performance tasks, either because they are not found or not examined. When signed heading errors are considered males demonstrated considerably more left veering than females. In fact, females veered slightly to the right. These findings are similar to the gender differences in turning bias reported by Mead and Hampson (1996) who found an overall turning bias favouring rightward turning with females showing a greater propensity for this direction. Although veering cannot be compared directly to turning bias, there may be some association between the two types of behaviours. The left veering tendency of our participants was also greater for target locations that were situated in the right half of space and was greatest for those in the non-vision group even though all groups responded under the same conditions. This finding is not likely due to either a body alignment or an orientation problem because left veering persisted despite the fact that body orientation prior to non-visual locomotion was checked by the experimenter to be straight-ahead. Moreover, no direction bias could have been introduced while participants were acquiring information about the targets' locations because they were randomly presented. Veering has been well documented in both the blind and blindfolded sighted individuals (e.g., Klatzky et al. 1990; Cratty, 1965; Harris, 1967; Rouse and Worchel, 1955).

Distance and Heading Error Compared to Performance by Chance

Navigation parameters like heading and distance must be correctly estimated if a traveler is to accurately return to a previously visited location that was learned without vision. Although the non-vision group in this study had difficulty estimating both parameters, distance was reproduced with more accuracy than heading, which was no different than that expected from chance performance. This suggests that distance estimation may be better than heading estimation for this type of task under the present conditions. The general heading error produced by the non-vision group may be partially explained by the restricted range of target headings that were used; the organization of the target locations was such that the most eccentric target was only 15 ° to the right of 90°. This was a limitation of the design that we did not foresee.

EXPERIMENT 2

The responses produced by participants in the non-visual group of experiment 1 suggested that distance was estimated more accurately than heading. Because information about distance and heading are acquired at the same time during non-visual locomotion, distance and heading information had to be examined independently from each other. Experiment 2 examined participants' ability to estimate traveled distance, independent of direction, with and without vision.

In order to return to a location in space that one has previously visited without vision, the distance and the direction (heading) to that location must be determined from sensory information available at the time of travel. Along with information from efference copy and somatosensation, separate vestibular sensors encode distance and direction (the otoliths and semi-circular canals, respectively). At this level, information about these two parameters is computed relatively independently. Experiment 1 required participants to reproduce *both* the distance and the direction components of their non-visual travel. Results suggested that non-visual information alone was not quite sufficient to allow an individual to accurately reproduce the distance and heading needed to return to a previously learned location. The absolute heading error produced by the non-vision group was off by approximately 10 ° and was greater than that expected had individuals received no information about target location. On average, distance was underestimated but the distance error produced by the same group was better than that expected from chance performance. It was suspected that reproducing both distance and direction simultaneously might have contributed to such errors. Thus, experiment 2 was designed to examine the ability to estimate the distance of a target when heading was held constant. As well, we compared perceptual and performance estimations of distance.

METHOD

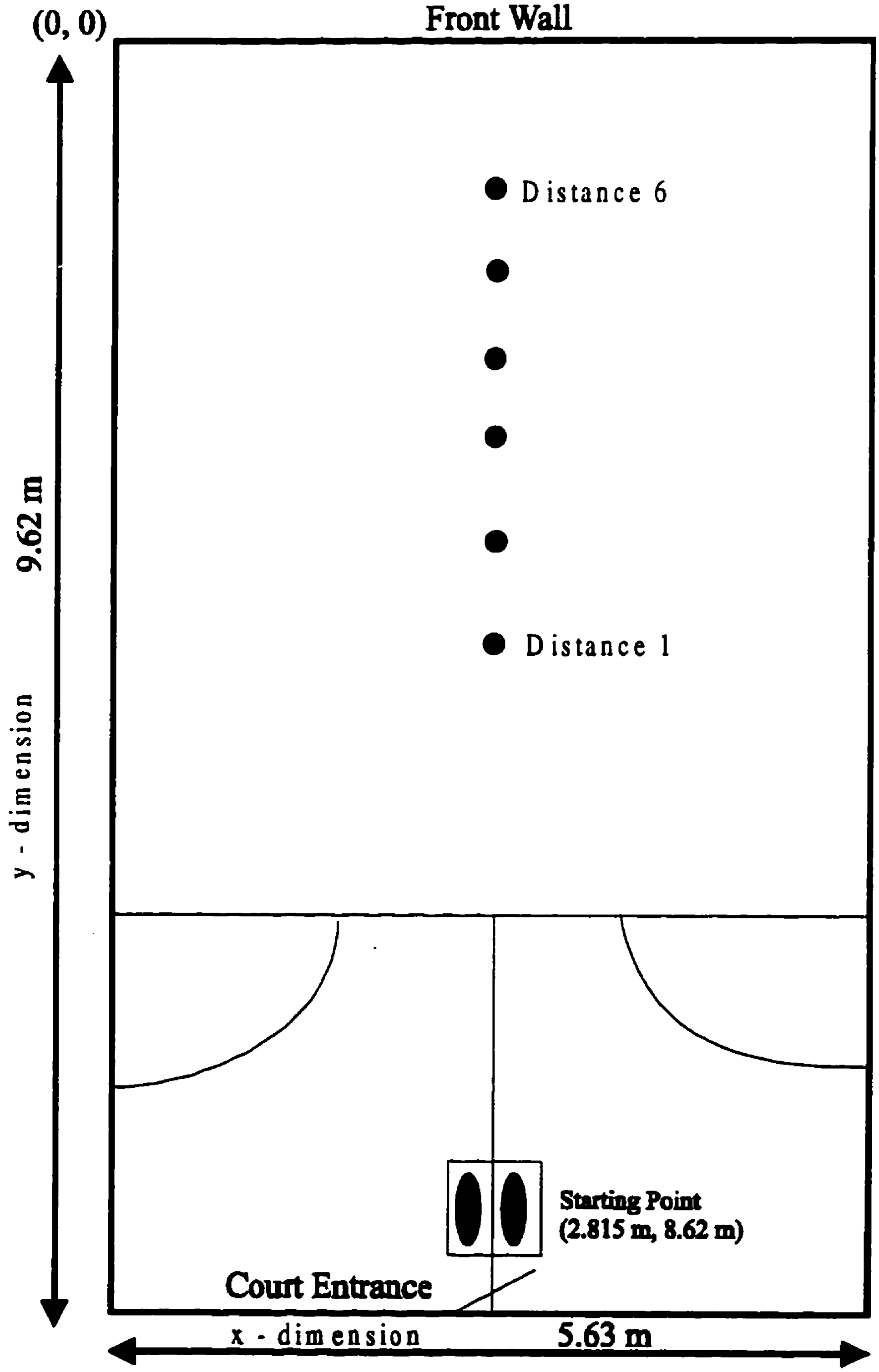
Participants and Apparatus

Twenty-four men and women undergraduate students from the Department of Psychology at the University of Waterloo participated in the study. Participation was voluntary but students in Introductory Psychology received course credit. Some of the participants from experiment 1 went on to complete experiment 2. Experimental trials were conducted within the same squash court described in experiment 1 and the same video camera set up was used to record all trials. The blindfold and earphones and the method by which participants were led to the target distances were the same as in the previous experiment.

Procedure

Participants were randomly assigned to either a vision group or a non-vision group and estimated six different randomly presented target distances. Measured from the participants' toes, target distances ranged from 4.3 m to 7.1 m and varied in the y-dimension only (Figure 6). Target distances for the vision trials were identified in the same manner as target locations in experiment 1. Participants in experiment 1 performed the distance estimation task shortly after the navigation trials of experiment 1. Standing at the starting position, participants in the vision group turned their back to the workspace until the target was placed at the appropriate distance. They then turned around and verbally estimated the distance from their feet to the target. Acceptable distance units were meters or feet. Participants faced the wall again while the next target

Figure 6. (Experiment 2). Scaled bird's-eye view of the court dimensions, location of target distances and starting point.



was being placed. Participants in the non-vision group were given practice walking without vision prior to testing. They were then guided from the starting position to a target distance and reported how far they thought they had walked. Following each response they were led back to the starting position and given a few seconds rest prior to the next walk. In order to prevent counting footsteps during the outbound and returning legs of the journey, participants in the non-vision group were asked to count down from 100 and pair each number with an animal ("One hundred bears, 99 horses, 98 cats...").

Data Analyses

Estimations of perceived distance were taken verbally but target distances and walked distances were taken from videotape. The conversion of data from pixels to meters was accomplished using the same transformations used to generate real world coordinates in experiment 1. Estimation error was calculated by simply subtracting the response from the target distance. Signed and unsigned (absolute) data were analyzed.

RESULTS

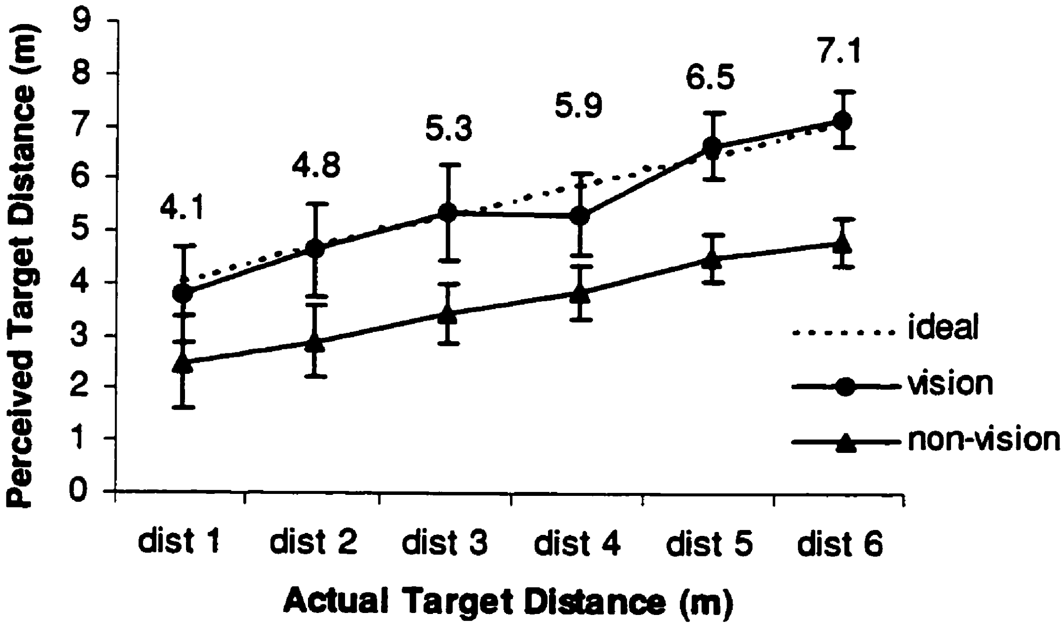
Unsigned Estimation Error

A repeated measures ANOVA on gender, previous group membership (i.e. from experiment 1), present group and distance only found a main effect of target location, F (5, 60) = 8.53, p < .005. Participants of both groups were better at estimating the closer rather than farther distances, although the vision group (M = 1.78 m, SE = 0.28 m) produced less estimation error than the non-vision group (M = 2.04 m, SE = 0.31 m).

Signed Estimation Error

A repeated measures ANOVA on the same variables showed a significant effect of group F (1, 12) = 10.49, p < .05. Figure 7 shows that, overall, the vision group (M = -0.071 m) estimated distance more accurately than those that received only non-visual information about target distance (M = -1.9 m). Although there was no statistical effect of gender F (1, 12) = 3.56, p > .05 and no interaction between group and gender, both genders underestimated target distance, females (M = -1.52 m) more so than males (M = -0.452 m). The analysis also revealed that group membership in experiment 1 interacted with gender and was just marginally significant, F (2, 12) = 6.32, p = .05. It appears as though this interaction is being driven by the fact that male and female participants in experiment 1 were influenced differently by being in the non-vision condition. Overall, males who were in the non-vision group for experiment 1 overestimated the distance of the target distance while females underestimated the same distances. Participants in the vision and both groups of experiment 1 did not perform differently in experiment 2. No other group-gender differences were found. However, we know from our findings in

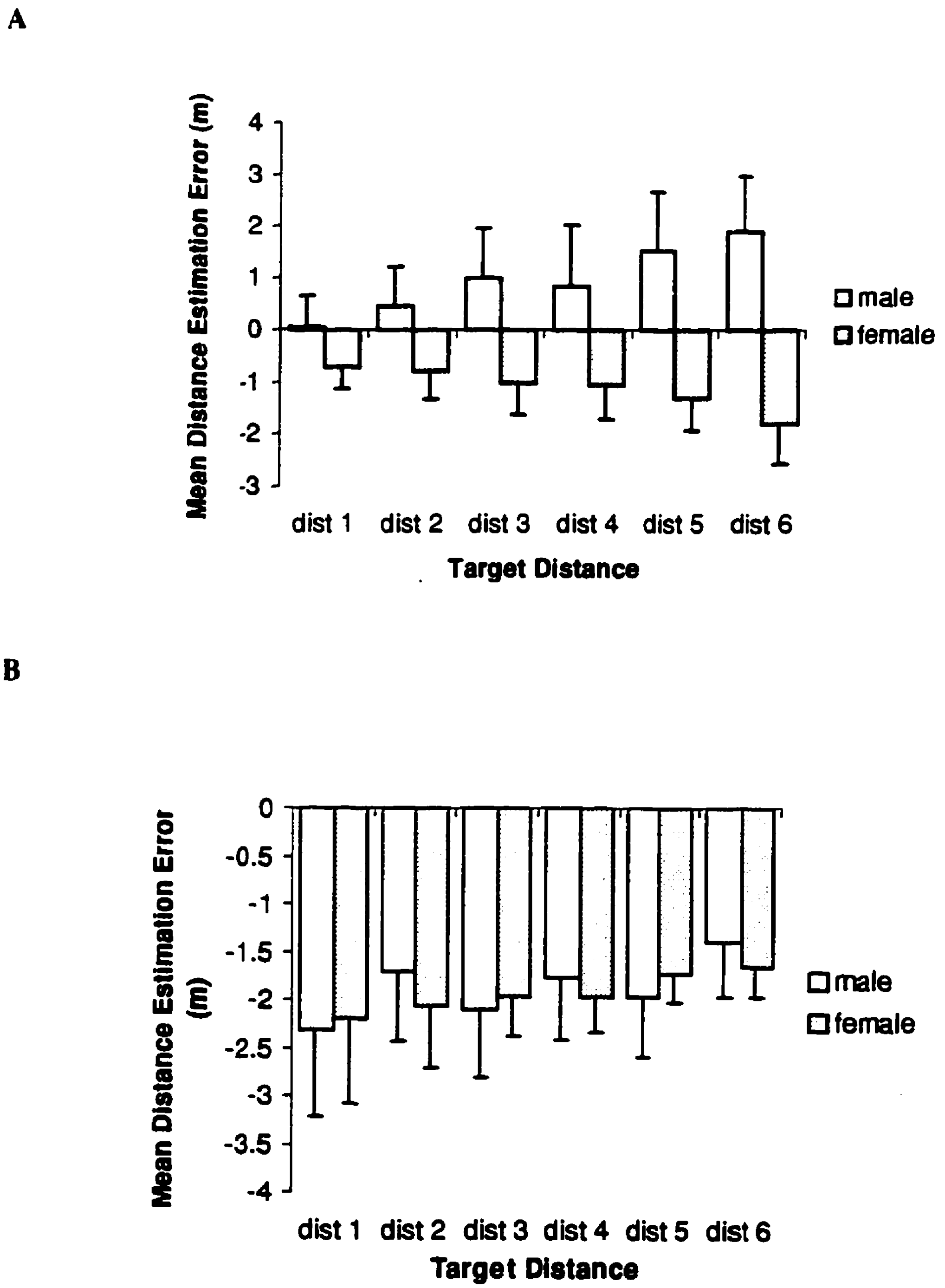
Figure 7. (Experiment 2). The relation between real distance and mean perceived distance for the vision and non-vision groups. Measured from the observer, distance 1 is the closest and distance 6 is the farthest.



experiment 1 that males and females perform differently on navigation performance tasks of this nature and so this result is neither surprising nor does it diminish the importance of the findings of the present experiment.

This analysis also revealed a 3-way interaction between group, gender and distance F (5, 60) = 3.32, $p < .05$. Although both males and females in the vision group were more accurate at estimating closer distances, males in this group overestimated while females in this group underestimated target distance, the magnitude of the over- and underestimations were comparable and not significantly different (see Figure 8a). There were no statistically significant differences in estimation accuracy between males and females in the non-vision group and their ability to estimate closer distances was no different from their ability to estimate farther distances (Figure 8b).

Figure 8. (Experiment 2). **A.** Gender differences in mean signed distance estimation for the vision group and **B.** non-vision group. Distance 1 is closest to the observer. A negative value represents an underestimation of target distance while a positive value represents an overestimated of target distance. Error bars indicate standard errors for each gender summed across target location.



DISCUSSION

The use of non-visual information in the perception of distance has been examined (e.g. Loomis et al. 1993; Klatzky et al. 1990) by leading blindfolded individuals to a target distance and asking them to verbally estimate the distance walked. The present experiment partially replicated previous findings, as we found an effect of target distance on estimation but we did not find the same over-under-estimation patterns. Instead our findings are novel and indicate that gender and sensory input differentially affect distance estimation. Loomis et al. (1993) led blind and blindfolded sighted individuals along a straight path for 2, 4, 6, 8 or 10 m and after the distance had been traversed, individuals gave a verbal estimation of the distance they thought they had traveled. No group differences were revealed but there was a distinct tendency to overestimate short distances (2 m) and underestimate longer distances (4 - 10 m). Klatzky et al. (1990) found similar results with distances between 4 to 12 meters.

The Effects of Non-Visual Sensory Input on Distance Estimation Accuracy

When vision of the target was provided, participants' perceptual judgments of distance were, on average, significantly more accurate than the distance estimates of those who were non-visually led to the target distance. In addition, the vision and non-vision groups differed on their signed estimates of each target distance; estimates based on non-visual information about target distance were consistently and significantly underestimated compared to judgments based on visual information. The importance of vision to accurate distance estimation is evident from the uniformly large distance underestimations for all target locations produced by participants in the non-vision condition. In contrast, participants in the vision group demonstrated the ability to estimate the distance of closer targets better than farther ones.

Females in the vision condition underestimated every target distance while males overestimated. This gender difference may be attributed to the fact that males and females applied different "perceptual rulers" to the distance they were asked to estimate. Males appeared to perceive a meter as shorter than it was while females perceived one meter to be larger than it was. Unlike other studies of this nature (see Loomis et al. 1993), our participants were not asked to base their estimations upon a previously learned standard distance. Although not necessarily indicative of a natural gender difference, it would appear that their estimates reflect some kind of difference in the way males and females use visual information to estimate distance. Interesting, however, is that the gender differences in visual estimates of distance were much larger than the estimates based on non-visual information; both males and females performed similarly when non-visual input was the sole source of information about target distance. This suggests that studying navigational abilities by employing tasks other than locomotion may not fully explain how navigation performance is accomplished. Moreover, this poses a problem for those who use non-locomotive tasks to illustrate sex differences in navigation and related spatial behaviours (Galea and Kimura, 1993; Ward et al. 1986). Navigation, which requires real world performance, cannot be thoroughly assessed by examining whether Euclidean or landmark-based knowledge is used to learn a novel map or whether differences in direction-giving strategies exist. Indeed, Thorndyke and Hayes (1982) reported differences in the kind of spatial knowledge that is acquired by studying maps versus engaging in actual navigation within an environment. The difference between estimating distance perceptually, in the form of a verbal response (experiment 2) and through performance (experiment 1) can also be seen by comparing the distance error of the non-vision and vision groups of experiments 1 and 2. The mean unsigned walked distance error of the non-vision group in experiment 1 was 0.846 m where as the mean unsigned distance estimation error for the same group in experiment 2 (verbal estimates) was 2.038 meters. A similar trend is seen in the vision groups of both experiments but the errors are lower.

When the findings of this second experiment are compared to the distance errors found in experiment 1, an interesting pattern emerges. In experiment 1, participants in the non-vision group stopped short of the target location perhaps because they perceived that they had walked farther than they actually had and had reached the target location. In experiment 2, people were led a distance of 7 meters without vision but perceived that they had walked about 3 meters. Although both responses required an estimation of traveled distance, estimating distance for subsequent reproduction of that distance (experiment 1) appeared to be different than estimating distance to render a verbal response (i.e. a perceptual judgement) about the distance traveled (experiment 2). This underscores the importance of the nature of the response output. Further, such an explanation is consistent with the distinction between perception and performance where sensory information is processed differently depending on whether an individual is acting in the world or representing the world (Milner and Goodale, 1995).

EXPERIMENT 3

Experiment 3 was designed to examine heading estimation independently of distance. There were 3 goals of this experiment. First, we assessed how well participants were able to utilize non-visual sensory information to estimate heading when distance was held constant. Because experiment 1 had revealed that the majority of participants tended to veer when walking without vision, the second goal of this experiment was to examine veering in more detail. Although veering is common in non-visual walking (Klatzky et al. 1990; Cratty, 1965; Harris, 1967), it led to an increase in heading error despite what may have been a very accurate initial heading or orientation. If, there is no difference between an individual's initial heading and travel heading, there is no veering and path reproduction is accurate. Therefore, we compared initial heading, before path reproduction, to the individual's travel heading at the end of their movement path to confirm that initial orientation was accurate. Because non-visual locomotion is a valuable tool in the study of navigation and because veering unquestionably has an impact on the evaluation of non-visual navigation, it was important to examine it more closely. In addition, initial heading is not often examined in this type of research. Third, it was noted in experiment 1 that target eccentricities were limited to angles between 75 ° and 105 ° and it was suspected that this lack of variability in target heading had an affect on the heading errors. Experiment 3 assessed heading estimation accuracy to more eccentric targets. This experiment also provided an opportunity to compare estimates of heading based on locomotion with those based on a verbal response. However, unlike experiment 2 where a perceptual estimate of a targets' distance was based on visual information, perceptual estimates of heading here were rendered verbally after a non-visual walk and performance data was acquired from participants' reproductions of the walked angles.

METHOD

Participants and Apparatus

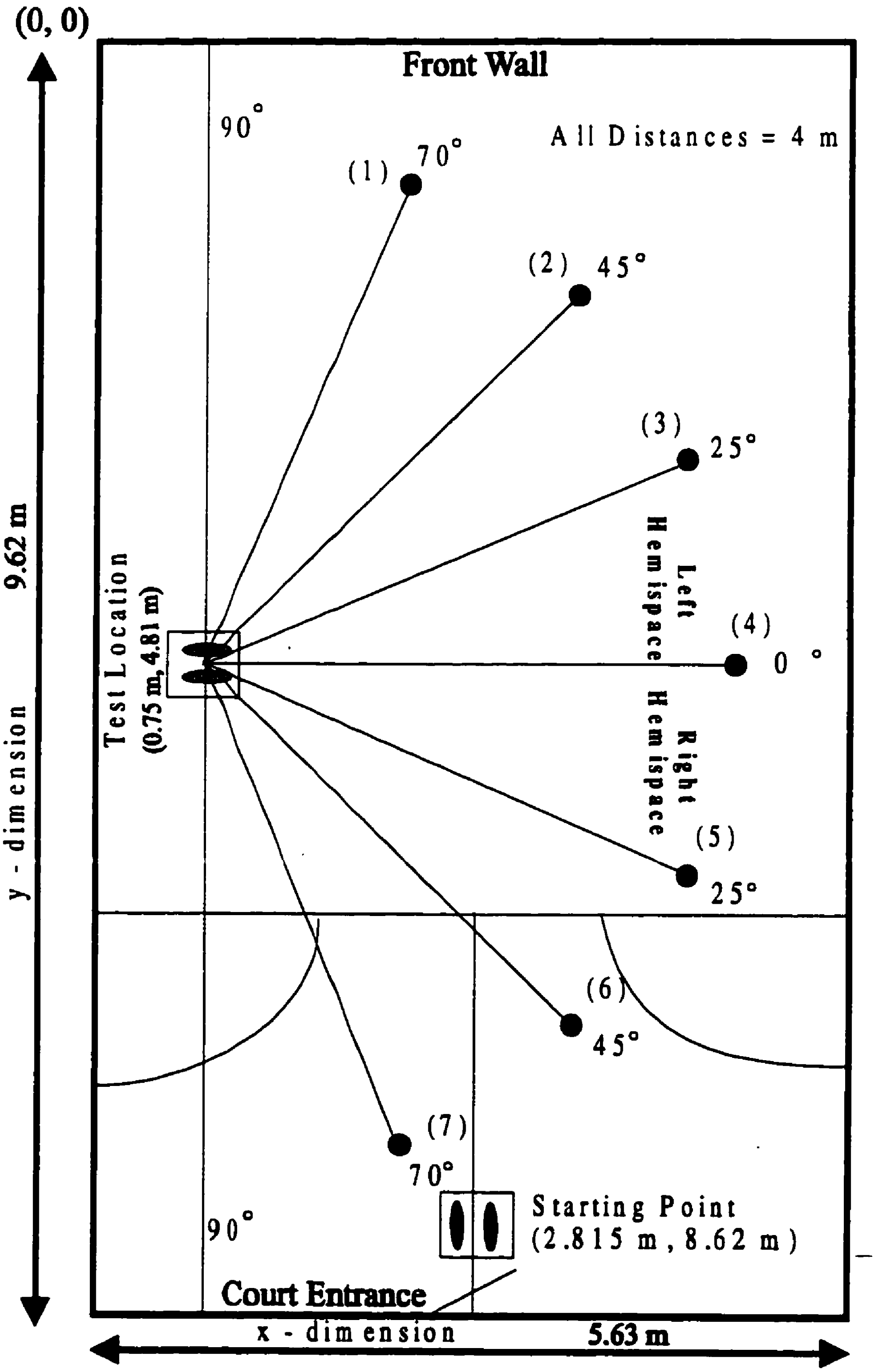
Twenty right-handed (10 male and 10 female) undergraduates from the University of Waterloo voluntarily participated in the study.

The location for the present experiment was the same squash court used for previous experiments. A pair of darkened goggles eliminated visual input and auditory information was dampened by a set of protective earphones. The starting location was located 1 m from the court entrance and the test location was approximately 60 ° to the left of and about 4.3 meters away from the starting location. Both locations were represented by the same set of raised foot impressions used in the previous two experiments and provided participants with some information about their orientation over the course of testing. Targets were positioned at 7 different angles. The range of the angles were, from left to right, -70 °, -45 °, -25 °, 0 °, 25 °, 45 °, 70 °, each 4 m from the test location (see Figure 9). They were labeled targets 1 though 7.

Procedure

Participants were divided equally into either a *perception* (verbal estimation) group or a *performance* (reproduction) group. After entering the court, which was empty save for the set of foot impressions by the door, all participants practiced walking blindfolded in order to get comfortable walking without vision (usually after walking the length of the court). Prior to being led to the test location, participants in the perception group were reminded about angles: "Just to refresh your memory, 0 ° is

Figure 9. (Experiment 3). Scaled bird's-eye view of the court dimensions, the location of the starting position and the test position and the trajectories of each target heading and their distances.



straight ahead of you, 90 ° is to the left (or right)." Participants were then asked to put on the blindfold and earphones so the experimenter could set up the test location. After the setup was complete, participants were led to the test location where experimental trials began. The blindfold remained on for the entire experiment and the sighted-guide technique was employed to lead blindfolded individuals to and from the target locations.

Perception Group (Verbal Estimation)

Standing at the test location, participants in this group were first smoothly turned in the direction they were to be led and were then led along an angled path to the target location. Because participants were facing straight ahead and some angles were rather eccentric, turning participants in the direction of travel before leading them to the target prevented the introduction of additional orientation error that could potentially affect heading estimation. For instance, leading participants to the target along an angled trajectory without first turning them in the direction of the target, might lead them to mis-estimate the target's true heading because it was originally misperceived at the outset of the journey. It is possible that this takes away from the similarity and generalizability of these results to errors generated in previous experiments. However, because we were striving to lower the variance associated with this kind of non-visual locomotive task, we felt that turning participants in the direction of travel was beneficial. After being led to the target location, participants were asked to estimate the distance and angle they thought they had traveled.

Performance Group (Reproduction)

Standing at the test location, participants in this group were first turned in the direction they were to be led and then were led to and from one target location at a time. After returning to the test location, participants were asked to first turn in the direction that they thought they were led and then to walk to the location that the guided walk stopped. Initial bearing was measured immediately after participants turned in the direction they thought they were turned prior to being led to the target location and heading was measured at the final point of their movement path. The reproduction of the heading also provided information about the ability to reproduce the distance traveled.

RESULTS

Travel heading was considered to be participants' final heading at the time they stopped walking. Initial heading was taken as the initial orientation prior to reproducing a given walk and was only measured for the performance group. Distance was defined as the total distance walked. For each target location, *travel heading error* (°) was calculated by subtracting the travel heading response from the ideal travel heading. *Initial heading error* (°) was calculated by subtracting the initial heading response from the ideal initial heading. *Distance error* (m) was the ideal distance minus the response distance.

Was performance of the performance group influenced by target locations?

In order to confirm that target locations influenced participants' responses, we calculated the slopes of each individual's response at all target headings. If participants' response headings were greater than chance, or, in other words, if their responses were related to the actual target heading, the mean of the group's slope would be significantly greater than a slope of zero. A one-sample t-test revealed that the mean of the slopes of heading responses was significantly different from a slope of zero or chance, t (9) = 21.43, $p < .001$, suggesting that participants did not respond in a random manner and that observed heading was dependent on actual heading.

Unsigned Travel Heading Error

When absolute heading error was examined, target eccentricity influenced travel heading error and there was a significant effect of target F (6, 96) = 3.37, $p < .01$ found.

However, a more detailed analysis revealed that target 4, which was positioned straight ahead at 0°, was driving this effect because the least amount of heading error was generated at this target (see Figure 10). When this target was removed from the analysis heading errors did not differ across target eccentricities and the mean unsigned heading error was 10.4 °. Figure 11 illustrates the relation between actual target heading and response headings for each group.

Unsigned Initial Heading Error

Recall that initial heading error could only be obtained for participants in the performance group as they were asked to turn in the direction they remembered to have been turned prior to reproducing the walked distance. The initial heading error for target 4 was not considered in the analysis because it was straight ahead. There were no significant effects of unsigned initial heading error but the pattern of errors indicates that the targets that required participants to turn farther from 0 ° but that are themselves closer to 90 ° (i.e. targets 1 and 7, both at 70 °), generated the lowest error (~7 °). Targets that were at 25 °, relatively close to 0 °, generated the largest errors (~131 °). There were no gender differences in initial heading error for any target locations. On average, initial heading error was 10.3 °.

Unsigned Distance Error

There was a significant difference between participants' estimations and reproductions of the target's distance and there was a significant effect of gender but these two results were qualified by a group by gender interaction, $\underline{F}$ (1, 16) = 6.42, $\underline{p}$ <

.025. Both males and females who were asked to verbally estimate the distance they had been led without vision (perception group) produced larger estimation errors (M = 1.6 m, SE = 0.25 m) than those that were asked to reproduce the same distance (performance

Figure 10. (Experiment 3). The mean unsigned heading error for each of the 7 targets across all participants. Error bars represent standard errors.

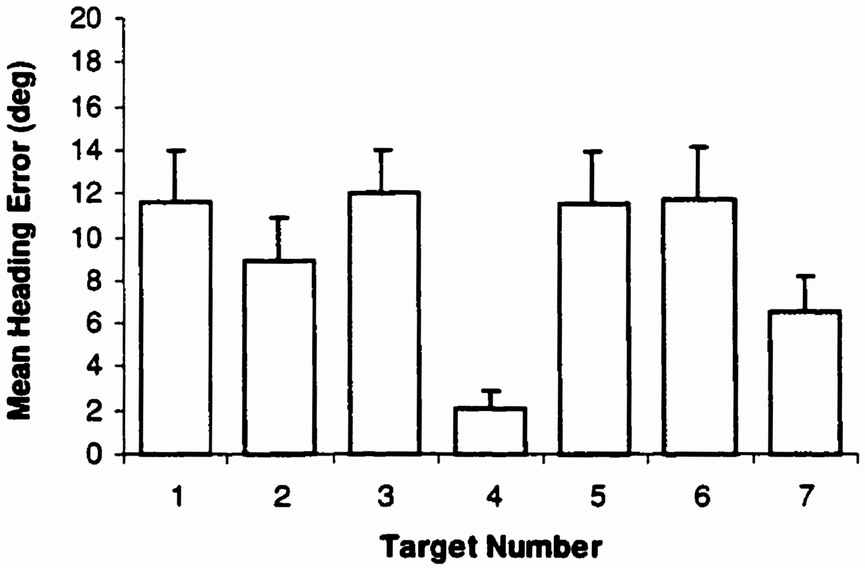
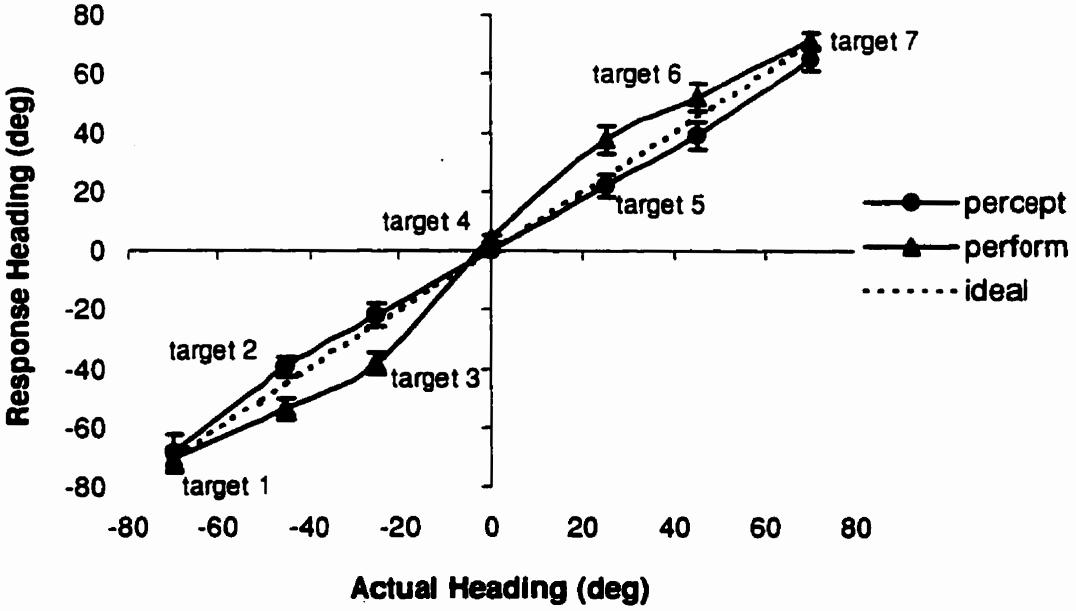


Figure 11. (Experiment 3). The relation between actual target heading and mean response heading for the vision and non-vision groups. All heading angles are unsigned. Targets 1, 2 and 3 are to the left of the observer, target 4 is straight ahead and targets 5, 6 and 7 are to the right of the observer. Error bars represent standard errors.



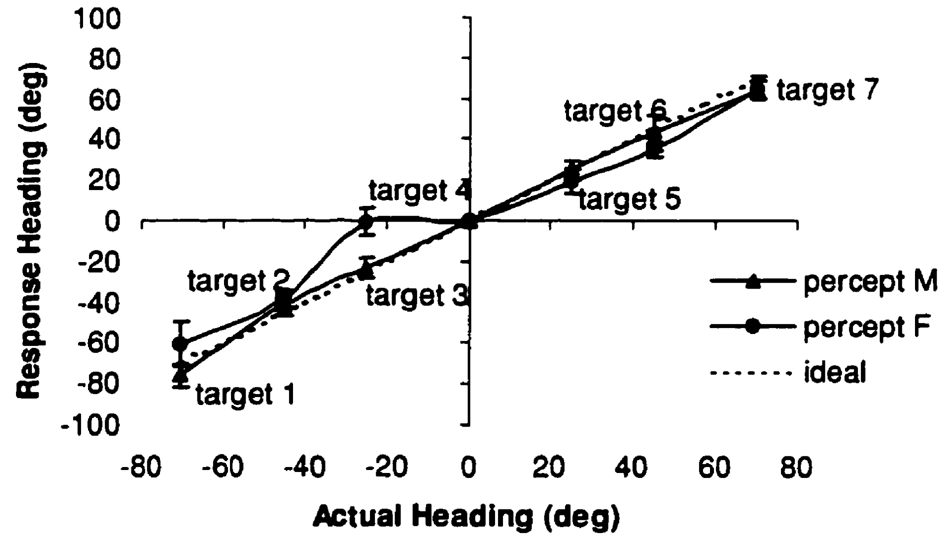
group) (M = 0.48 m, SE = .032 m). Females (M = 2.12 m, SE = 0.35 m) in the perception group misjudged distance significantly more than males (M = 1.08 m, SE = 0.17 m) in the same group, F (1, 8) = 7.01, p < .05. However, gender differences disappear when participants were asked to reproduce the distance they had been guided. Figures 12 a. and b. show the relation between actual target heading and response heading for each gender in perception group and the performance group.

Signed Travel Heading Error

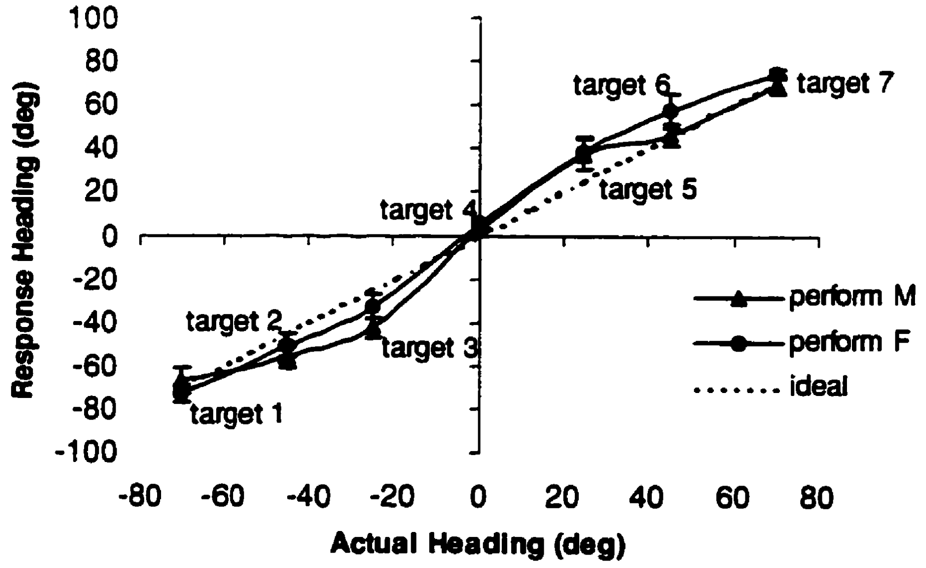
Signed travel heading errors indicate whether heading angles were estimated or reproduced to the left or to the right of the targets' true angle. Results show an interaction between target and group F (6, 60) = 4.81, p < .001, indicating that travel heading errors varied with target eccentricity and that the perception and performance groups responded differently. Participants asked to reproduce the heading towards the target reproduced target headings at 70 ° most accurately (targets 1 & 7), while targets at headings of 45 ° and 25 ° (targets 2, 3, 5, 6) were more difficult to reproduce. They responded to the left of the targets for targets in *left* hemispace and to the right of the targets for targets in *right* hemispace. In contrast, the heading estimations of participants in the perception group, who verbally estimated the direction of their walk, were biased to the right for targets in the left half of space and to the left of for targets in the right half of space. There were no significant differences in verbal estimations of walked heading or reproductions of walked heading between males and females for any target.

Figure 12. (Experiment 3). A. Perception Group. B. Performance Group. The relation between actual target heading and mean response heading for the vision and non-vision groups. All heading angles are unsigned. Targets 1, 2 and 3 are to the left of the observer, target 4 is straight ahead and targets 5, 6 and 7 are to the right of the observer. Error bars represent standard errors.

A.



B.



Signed Initial Heading Error

There was a significant effect of target F (5, 40) = 9.56, p < .001 suggesting that target eccentricity had an effect on initial heading accuracy. The pattern of initial heading errors appears to mirror the travel heading errors produced. Figure 13 shows that initial heading was very accurate for the most eccentric targets (targets 1 & 7) in both halves of space while targets at 25 °, which were the closest to 0 °, generated the largest initial heading error. One-sample t-tests showed that participants' initial heading for targets at 25 ° (targets 3 and 5) as well as target 6 (45 ° to the right) were significantly different from the ideal initial heading.

To assess whether participants veered during their walk we compared their initial heading with their final heading for each target. Paired t-tests revealed no significant differences between initial heading and travel heading suggesting that there was little or no veering in participants' reproduced paths (see Figure 14).

Signed Distance Error

There was no difference in participants' signed estimations or reproductions of the distance to the target location, p > 0.1. On average participants underestimated the distance they were guided by approximately 64 cm. This finding appears to contradict what was found for absolute errors – that verbal estimations of distance differ from reproductions of distance. In addition, signed distance errors produced by males and females were not different (p > 0.1) and this result differs from the unsigned data, which showed differences between the two genders. However, it is important to understand the nature of these two types of data: Signed distance errors will account for the over- and

Figure 13. (Experiment 3). Mean signed initial heading errors for each target summed across participants. A negative initial heading error represents a turn to the *left* of the ideal initial heading and a positive bearing error represents a turn to the *right* of the ideal bearing. Error bars represent standard errors.

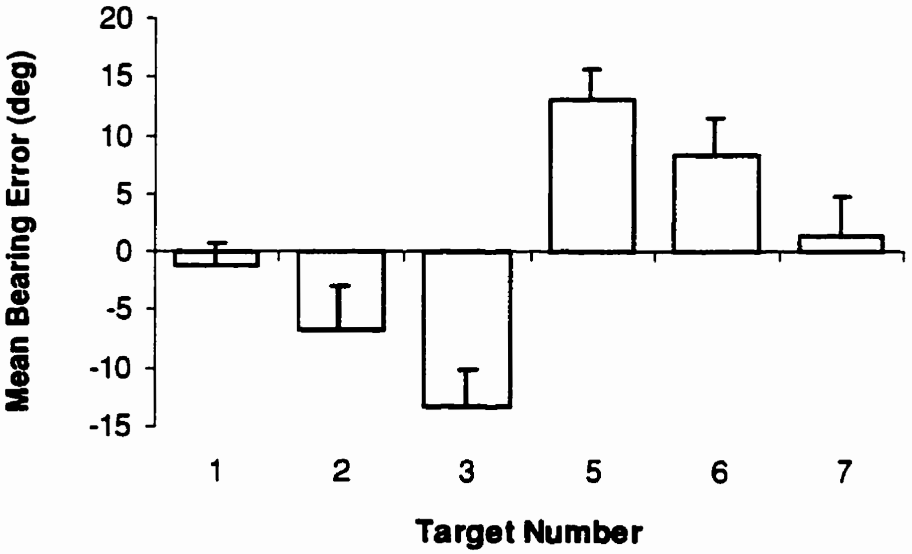
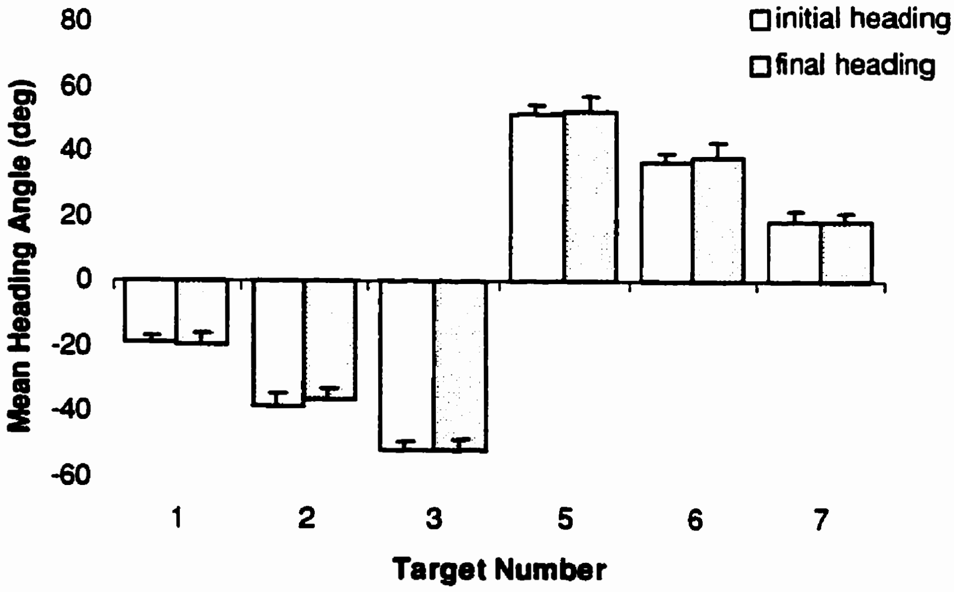


Figure 14. (Experiment 3). A comparison of the actual mean initial heading angle with actual mean final heading angle summed across participants in the performance group. All data are signed. Targets 1, 2 and 3 are to the *left* of straight-ahead and targets 5, 6 and 7 are to the *right* of straight-ahead. Error bars represent standard error.



under-estimations of distance in both estimation and performance while absolute distance error is a general measure of distance error. In this instance, there were no over-estimations made and all participants similarly underestimated the target, thus no signed differences were found.

DISCUSSION

Target Eccentricity and Heading Error

The ability of individuals to estimate or reproduce a given heading depended on the eccentricity of the target. Recall that the two goals of this experiment were to examine how well heading could be estimated when distance was held constant and how well targets at more eccentric angles could be estimated and reproduced after non-visual walks. The present experiment utilized targets that were at angles as small as 20 ° and as large as 160 °, whereas in experiment 1, target eccentricities were limited to 90 ° +/- 15 ° (see Table 3). It was suspected that the heading errors produced by participants might have been influenced by this limitation. Results of unsigned heading error indicated that indeed, target eccentricity had an effect on the amount of heading error produced by participants in both groups. The overall heading error was on the order of 10 ° and this was similar to the mean heading error produced by participants in the non-vision group of experiment 1 (9.7 °), where much of the error was due to targets of limited eccentricity. The pattern of signed heading error shows more clearly how target eccentricity affected performance. The performance group reproduced heading most accurately for targets closest to 90 °. The headings of targets located at 45 ° and 25 ° in either hemispace were reproduced with the least accuracy, albeit errors were slightly lower for targets at 45 °. When target heading was estimated verbally, errors did not vary as much with target eccentricity, although they were slightly larger for targets located at 45 ° and 25 °. On average, it seemed as if verbally estimating the heading of a target was easier than physically reproducing the heading towards the target as the signed errors of the perception group did not vary with target eccentricity as much as those of the performance group. Both groups received approximately the same input (non-visual information through locomotion) but one main difference between the groups was the response output required: One was a motor response (locomotion) while the other was a verbal estimation of a perceived parameter. The present results, which can be linked to the differences found between the two groups in the previous experiment, suggests an interesting relation between response accuracy, the type of sensory input received and the type of response output. Specifically, a verbal estimate of a visually perceived parameter (i.e. distance) is most accurate; a verbal estimate about the characteristics of a non-visual walk is much less accurate while non-visually <u>reproducing</u> a heading or distance after a non-visual walk produces the largest error in estimation. Unfortunately because there was no group in the present experiment that visually estimated target heading, we cannot say for sure that heading would be estimated with the same accuracy as distance. Similarly, had there been a group in experiment 2 that reproduced the distance they were led without vision, we would have been able to make direction comparisons to that same group here. Despite this shortcoming, there is something intriguing about response accuracy and its relation to the type of sensory input received and the response output required.

One way participants may have attempted to reproduce target heading was to make note of how close the heading of the traveled path was to the arms of a right angle which can easily be referenced (Sadalla and Montello, 1989). If this were the case, targets closest to 0 ° or 90° would be most accurately estimated. Sadalla et al. (1989) studied turn angle estimation after participants walked a path under conditions of reduced vision (no peripheral vision and forward vision restricted to 0.5 meters).

Participants were led along a straight path, turned at a specified angle and then completed the path. It was hypothesized and found that estimation errors increased as a function of the angle's distance from right angle reference axes. This finding is similar to that which was found in this experiment; angles closer to 90° were better estimated than those farther away from right angle axes. However, target headings of 25 °, which were the closest to 0 ° in this experiment, generated the largest errors. The target heading closest to 0 ° used by Sadalla et al. (1989) was 15 °. Although this target angle was only 10 ° larger than the target heading used here, it may have been close enough to a right angle to be easier to estimate and reproduce. An alternative explanation may be that when participants were turned in the direction they were to be led, a turn of 25 ° (i.e. to the target 3 or 5) did not provide as much rotational information about orientation as a turn of 70 ° (i.e. to targets 1 or 7). As a result, participants could better "guesstimate" their initial heading after the larger turn than the smaller turn which led them to estimate the headings towards the targets 1 and 7 with more accuracy. That participants in the present experiment did not receive vision during the experiment suggests that the determination of heading can be done without visual input but that it is dependent on the eccentricity of the target to be estimated, a finding that supports Sadalla et al. (1989). Klatzky et al. (1990) found that when participants reproduced turns of differing angles, their responses were pulled towards a known referent like 0 ° or 90 °.

Initial Heading and Travel Heading

Few studies of non-visual navigation have assessed heading prior to a locomotive response, a measure that is referred to in this study as initial heading. It was found that initial heading was useful at predicting travel heading for participants in the performance group as their signed initial heading errors were comparable to their signed travel heading errors. Although there is limited literature against which initial heading errors found in the present study may be compared, participants' initial heading may be compared to their own travel heading to examine more closely the phenomenon of veering during non-visual locomotion. If initial heading does not differ from travel heading, no veering has occurred during locomotion. It was expected that these two measures would be similar but based on results from experiment 1, it was not known to what extent initial heading and travel heading would correspond. Results showed that, despite error in travel heading estimation and reproduction, this prediction was borne out; participants were, on average, within 1.5° of their initial heading by the time that they reached the perceived target location. Klatzky et al. (1990) determined veering in her participants by measuring their heading after the first 2 meters of travel and the final heading for the last 2 meters of a non-visual walk. She found that, at a normal walking speed, there was a difference of about 10 ° between the initial 2-meter heading and the final 2-meter heading which translated to veering 10 ° off the ideal path heading. The amount of veering found by Klatzky et al. is similar to the magnitude of veering produced by the non-vision group from experiment 1 (9.7 °). However, the length of the workspace used by Klatzky et al was approximately 5 m larger than that which used in all of our experiments and so the extent of veering might be expected to be less over a smaller distance. It is possible that the reason for the correlation between initial heading and travel heading in this experiment was because participants in the present experiment were first turned in the direction that they were to be led prior to learning the location of the target. Moreover, participants were asked to reproduce this turn prior to reproducing the path and the additional information about orientation may have provided what was needed for accurate reproduction of the target path. In experiment 1, participants were simply led to and from the target location along an angled trajectory. That veering was virtually absent in this study suggests that participants in experiment 1 received ambiguous information about orientation and path heading at the onset of the outbound journey to a target even though angular stimulation was sufficient to perceive the direction of the walked path. The findings about initial heading indicate that having a good sense of one's initial heading prior to learning a simple linear route is very helpful in encoding the direction of travel for subsequent path reproduction or navigation.

Distance Errors: Gender Differences and Perception versus Performance

Participants in the perception group were asked to provide verbal estimates of distance and individuals in the performance group provided measurements of distance when they reproduced each target heading. It was found that the distance errors in this experiment were dependent on whether distances were verbally estimated or whether they were reproduced. Participants who reproduced the paths they were led without vision were more accurate than those that verbally estimated the distance they were led. In the discussion of experiment 2, it was suggested that there might be something fundamentally different about a response that is verbally rendered as compared to one that requires locomotion performance. Although they may not be the most accurate categorizations, we have labeled these two responses as perception, which is understood as one's perception of the magnitude of the parameter of interest and performance because one actively produces the perceived magnitude of the parameter. When the unsigned distance errors of participants from the perception group ($\underline{M}$ = 1.6 m) of the present experiment were compared to those of the performance group ($\underline{M}$ = 0.48 m) the differences are clear; those that verbally estimated performance were less accurate than those that reproduced the distance they were led. This does not appear to be a chance finding as participants in the non-visual group of experiment 1 produced a similar distance error (unsigned $\underline{M}$ = 0.85 m). It is possible that leading participants to and from the target location gave them two opportunities, one on the outbound journey and one on the return journey, to estimate the distance to the target. However, participants in Loomis et al.'s (1993) non-visual navigation experiment were accurate at reproducing the distances of a number of traveled paths after only one chance at encoding distance.

An alternative and perhaps more interesting explanation of the difference between the perception and performance groups is related to the response output used by each group. It is possible that reproducing the distance one has traveled is less biased than providing a verbal response of the perception of distance. Further evidence to support the idea that estimations of distance are somewhat dependent on response output was found when distance errors produced by males and females in the perception group were compared to errors of males and females in the performance group. Differences between the genders were clear in the perception condition, where distance traveled was verbally estimated but this difference disappeared when males and females reproduced the distance traveled. Despite the differences in protocol, the findings of the present experiment may also be compared to what was found in experiment 2. Male and female participants who were asked to estimate the distance of a target (perception group) generated quite disparate distance errors. However, when they were led the distance they were to estimate, the differences in distance estimation disappeared. When asked to verbally report on the perceived magnitude of distance, participants that did not actively engage in experiencing the distance (experiment 2) or in reproducing the distance (present experiment) differed in their estimations from those that did. The present experiment along with the previous experiment illustrates the potential difference between verbal and locomotive response outputs; estimating distance and direction verbally is not the same as reproducing those variables through locomotion.

EXPERIMENT 4

The findings from experiment 1 showed that people were able to set and hold a course to a target they had previously seen but had difficulty returning to a target whose location had been learned non-visually. It was concluded that non-visual locomotion did not provide enough information about the distance and direction to the target. However, another plausible explanation is that not enough spatial information was provided by a single target location to allow participants to build a detailed spatial map. Perhaps additional spatial structure is needed when space is to be represented or learned without vision for subsequent navigation within that space. A way to test this is to assess whether people are able to build a non-visual representation or map of *multiple* spatial locations. Experiment 4 asked individuals to form and maintain a spatial representation of an array of <u>five</u> objects whose locations were learned either visually or non-visually. Spatial information and path integrative ability were assessed by asking individuals to point in the direction of or walk to the location of the learned objects *after they were led to a novel location in space* without vision. The integrity of participants' representations of space at the novel location was then tested. This experiment was the first explicit comparison of pointing and walking.

Rieser et al. (1986) and Loomis et al's. (1993) replication of Rieser's work examined the degree to which prior visual or non-visual information of an array of objects facilitated access to knowledge of spatial structure. The study measured an individual's ability to update their position and the relative positions of the objects they had previously learned without vision. In addition, the integrity of participants' spatial representations was examined by testing their knowledge of space after moving them to a novel location. Non-visual pointing accuracy from this novel location was used as a measure of participants' knowledge of the spatial arrangement of objects. Their results indicated that non-visual information, based on efference copy and proprioception from locomotion, provided sufficient information to allow participants to update self-to-target spatial relations in order to point accurately to the learned targets from the new position. This study provided an ideal framework for investigating an individual's ability to develop a representation of multiple locations in space.

Because this research seeks to understand how non-visual sensory information from locomotion contributes to our ability to represent space for subsequent non-visual navigation, we asked something that Rieser et al. (1986) did not address in their study. Are the internally generated non-visual spatial representations that enable individuals to point to objects from a novel location sufficient to enable people to walk to the same targets? Haber et al. (1993) have indicated that using a body part (nose, chest, finger) or an extension of a body part (cane, stick) is the most accurate method with which someone without vision may indicate direction. However, even though pointing is locomotive in nature, it is not locomotion per se and there is nothing to suggest that pointing is the best and least biased measure of spatial knowledge for the purposes of navigation. To appreciate this, consider that blind individuals, who navigate by locomotion successfully, rarely use pointing to indicate the location of an object unless it is within very close proximity (Veraart and Wanet-Defalque, 1987; Wanet and Veraart, 1985).

Casual comparisons were made between the pointing heading error produced at baseline by participants in Rieser et al.'s study and the walked heading error produced by participants in the non-vision group of experiment 1 of this thesis. It was noted that the heading errors produced by participants in our experiment, where walking was used to indicate knowledge of target location, were slightly lower than the heading errors produced by Rieser's participants who pointed to indicate target location. Although there were a number of methodological differences between the two studies, we were convinced that pointing and walking were different measures of a person's representation of space. When participants in Rieser's study were led to an unknown novel location and asked to point to the same targets from this location, the accuracy of their pointing performance decreased considerably. We wondered whether this would occur for a locomotive response output.

The general purpose of this experiment was to examine how well individuals could form and maintain a spatial representation of an array of five objects whose locations they learned with or without visual input. It was hypothesized that, when measuring an individual's representation of space, heading errors would be dependent on the type of response output required. It was also hypothesized that when participants are asked to point without vision to a previously learned target location their heading errors will be different than if they were asked to walk without vision to the same target. The methods of this experiment allowed us to assess whether individuals could use path integration to accurately update their position in space with respect to a known origin after being led to a novel location in space. To assess the relative contribution of vision to this task, we included a group that received only visual information about the object locations so that their performance could be compared to those that received non-visual input. Based on findings from experiment 1, we expect differences in the magnitude of errors generated by the vision and non-vision groups. Finally, participants were asked to draw a map of their representation of the experimental space after completing the experiment. This was included to explore whether an individual's perception of space, as indicated by their drawing, was in any way related to their performance.

METHODS

Participants

There were a total of 48 (24 males, 24 females) University of Waterloo undergraduates in the present study. All participants received course credit for their voluntary participation. Participants were all right handed.

Apparatus

All trials took place in the same indoor squash court used in experiments 1, 2 and 3. The starting point and the novel location were indicated by raised foot impressions[3] fastened to the floor of the court. Five common objects, a baseball, a shoe, a beer bottle, a book and a Kleenex box, represented the target locations (Figure 15). This was the left-right order of the targets as seen from the starting point. All targets, except for target 4, the book, were randomly located at different locations on the floor of the court and could be easily viewed and recognized from the starting position. Because experiment 1 showed that there was a tendency to veer when walking without vision, target 4 was located directly in front of an observer standing at the novel location. Thus, when asked to walk to this target during the test phase, participants' veer

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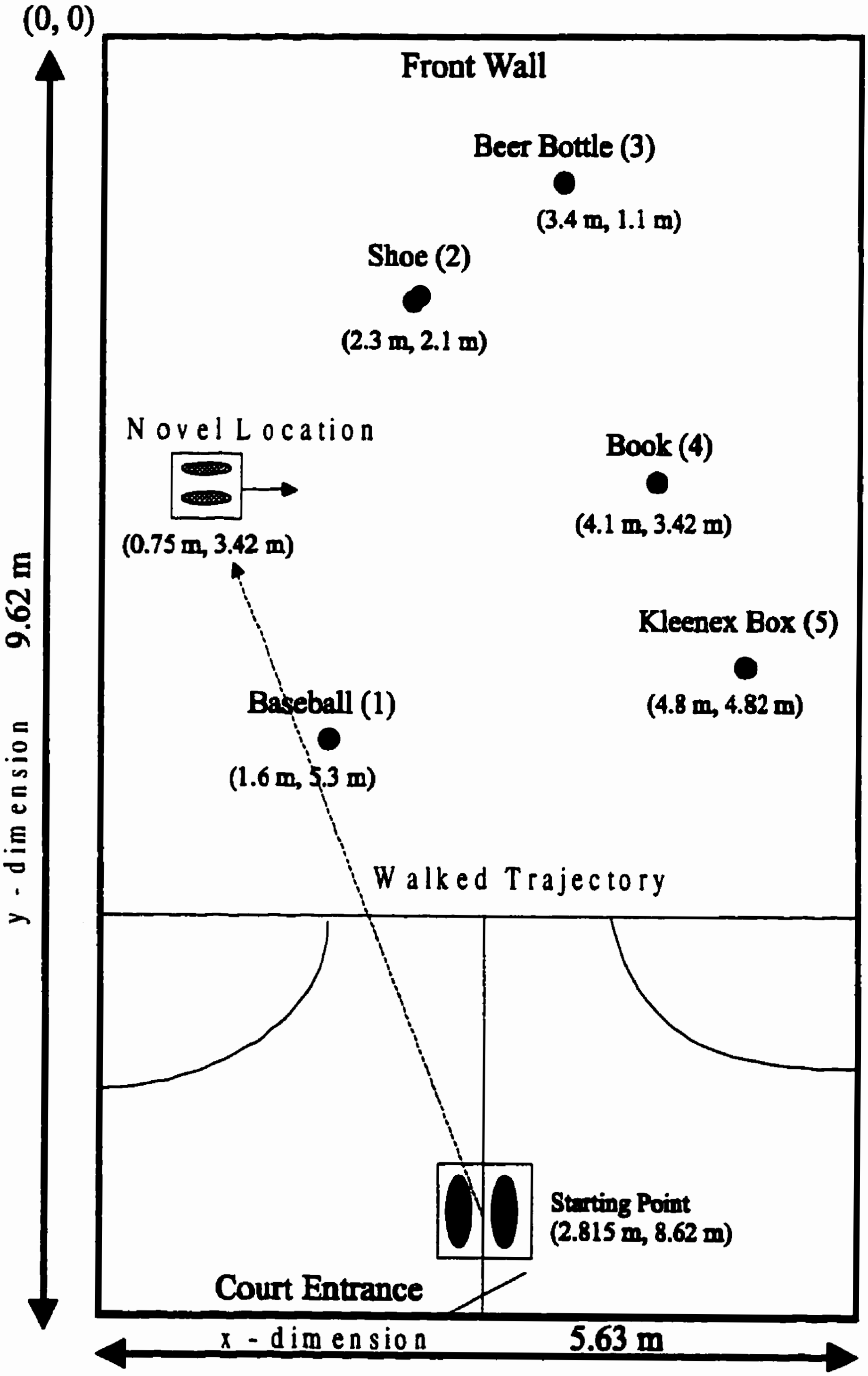
[3] Because the novel location (test location) was represented by a set of raised foot imprints it will sometimes be referred to as 'the novel feet'.

would not be the result of the target's location. The blindfold was a set of darkened goggles and protective earphones dampened auditory information.

Figure 15. (Experiment 4). Scaled bird's-eye view of the squash court dimensions, the location of the starting point (baseline position) and the novel location (test position) and 5 targets. The arrow at the novel location represents the orientation of participants at test and the ideal walked heading towards target 4. The walked trajectory represents the heading of the non-visual walk to the novel location.



Design and Procedure

The methods of the present experiment are modified from Rieser et al. (1986). The experiment was broken up into a baseline or training phase and a test phase. The baseline phase measured the extent to which participants learned the locations of the targets and the test phase assessed participants' spatial knowledge of their position in the court and the locations of the targets after they were guided to a novel location without vision. At baseline participants were randomly assigned to either a vision group or a non-vision group. First, at test, half the participants from each group were assigned to the pointing group and the remaining participants from each group were assigned to the walking group. This division was based on the type of response that was required during the experimental phase of the experiment. Additional changes to Rieser's protocol are noted below. Instead of using a metal pointer mounted above a protractor to indicate the perceived location of a target, participants made a more natural pointing response by pointing to each target location with a hand-held laser pointer. This method was employed because using such a pointer approximated pointing responses in the real world. Using a laser pointer also led to more accurate pointing responses compared to other methods (Haber et al. 1993). Another exception was that instead of including an imagination condition, we included a walking condition since we were very interested in navigation performance rather than mental transformations of space. In the walking condition, participants were asked to walk to the location of one of the previously learned objects from the novel location. Similar to the protocol in Loomis's paper (1993) but not mentioned in Rieser et al. (1986), all participants, as part of the learning phase, memorized the names of the five objects in left-to-right order prior to learning their spatial locations. One reason for this procedure was that it made the task easier for the participants and also ensured that responses were not confounded with poor memory for the names of the objects. Finally, participants were asked to transfer their spatial knowledge to a map on which they were asked to draw the locations of the objects and the novel location. This, we felt, was one way to examine participants' self-location after a linear translation as well as compare their spatial perceptions of the object array with their performance.

All blindfolded walks were carried out using the sighted-guide technique developed for leading the blind where the person being guided held onto the upper arm of the experimenter. All participants were given practice walking without vision and were allowed to practice using the laser pointer prior to starting the experiment.

BASELINE

Training, Assessment and Scoring

Vision Group

Prior to viewing the spatial layout of the five target objects, the experimenter recited them in left to right order. Participants memorized the names and spatial order of the targets to ensure that they would be remembered for the test phase. Participants then viewed the arrangement of target objects in the fore part of the court and were asked to remember their locations. After 15 seconds, they were blindfolded and instructed to point the laser in the direction of the target that was randomly named by the experimenter. Because there was a natural tendency to move the trunk along with the arm while pointing, participants were instructed to move only their arm to prevent this kind of pointing angle error. It was important that the laser beam fall on the wall for measurement purposes and participants had no difficulty pointing in this manner with some training. All targets were presented randomly. Pointing locations were recorded by placing a mark on the wall where the laser beam fell and beam coordinates were manually measured in meters. Pointing response angles were later calculated using these coordinates. Baseline pointing errors were calculated by subtracting the response angle from the ideal pointing angle for each target. Signed and unsigned (absolute) pointing errors were generated.

After responses were recorded, participants were given an additional 15 seconds to view the layout of the targets before the test phase. The targets were then removed and participants were blindfolded and guided without vision to a novel location

Non-Vision Group

Similar to the vision group, participants in the non-vision group memorized the names and the spatial order of the target objects. Because vision of the target location was not allowed, the locations of the target objects were learned by guiding blindfolded participants to and from the location of each object in the order that they were memorized (i.e. first they were guided to the baseball and back to the starting point. Then they were guided to the shoe etc...). During the outbound and return legs of the journey to each target location, the experimenter read a list of random words aloud and participants had to repeat them. To prevent participants from using the beat of the spoken words to count their steps, different words were used for the outbound and return legs of each target and the experimenter paused for random lengths of time between words. After target locations were learned participants were instructed to point the laser in the direction of a target that the experimenter had named at random. Pointing locations were recorded by placing a mark on the wall where the laser beam fell and beam coordinates were manually measured in meters. Pointing response angles were later calculated using these coordinates. Baseline pointing errors were calculated by subtracting the response angle from the ideal pointing angle for each target. Signed and unsigned (absolute) pointing errors were generated.

After these baseline responses were recorded, participants were guided to the location of each target one more time. Once back at the starting position they were given a short rest and then were guided, without vision, to a novel location in the court.

TEST

Assessment and Scoring

After participants reached the novel location they were oriented to face the inside of the court. Blindfolds were maintained for the entire test phase.

Pointing Group

To test the integrity of participants' spatial representations and their ability to update their new position in the court, the experimenter named an object at random and participants were instructed to point in the direction of the target *based on their new location*. To ensure that the task was understood, participants were reminded that only they, not the targets, had moved. After responses were recorded participants were led back to the starting point. Half the participants from the vision group and half from the non-vision group pointed to targets during testing.

Pointing responses were measured in the same manner as baseline pointing responses. Pointing heading errors at test were calculated by subtracting the response angle from the ideal pointing angle for each target. Signed and unsigned (absolute) pointing errors were generated.

Walking Group

Participants were told that in order to test their spatial representations of the previously learned object locations, the experimenter would name one object and they were to walk, unaided and without vision, to the location of that object. Target 4, the book, was the only target location participants were required to walk to as this target was located straight ahead of them from their position at the novel feet. Blindfolds were maintained and participants were led back to the starting point. Half the participants from the vision group and half from the non-vision group walked to targets during testing.

Two scores were generated from analyzing the test responses for the walking groups: Walked distance and walked heading. The position of each participant when they stopped walking was taken as the perceived location of target 4 and the x-y coordinates (in meters) of this location were measured. Walked distance was the total distance walked from the novel location to where the participant stopped walking and distance errors were calculated by subtracting the response distance from the ideal distance to the target from the novel feet. Walked heading was the heading angle of the walked response and heading errors were calculated by subtracting walked heading from the ideal heading (i.e. straight ahead). Both walked distance and walked heading errors of the vision walking group were compared to the same errors of the non-vision-walking group and signed and unsigned (absolute) pointing errors were generated.

Pointing Heading vs. Walked Heading

Because the main goal of this experiment was to compare the difference in accuracy between pointing heading and walking heading, an important analysis was to compare pointing heading errors with walked heading errors at test.

Map Drawing and Scoring

After the test trials were completed the blindfold and earphones were removed. Prior to giving feedback about performance, participants were given a schematic drawing of the court (see Appendix 1) and were asked to draw the following items on the map: The locations and labels of each target, the location of the novel feet and their perceived orientation at the novel feet. At the time of drawing, the novel feet and target objects were not in view.

Because the maps given to participants to fill in were not drawn to scale, all coordinates were converted to the scale of the court. *Perceived walked distance* from the starting point to the novel location was gleaned from the maps by extracting the x-y coordinates of the perceived novel location. This was then compared to the ideal distance to the novel location.

Heading Error Using *Perceived* Self-Location at Novel Feet and *Real* Targets

It was suspected that participants' performance at test might have been related to where they perceived themselves to be at the novel location. By accounting for participants' perceived position after the non-visual walk to the novel location, we equated the vision and the non-vision groups prior to test. Heading angle at test was then re-assessed by calculating a new ideal heading angle using the coordinates of their perceived location and the real target locations (drawn feet-real targets). Heading error was calculated by subtracting their response from this new ideal heading angle.

Heading Error Using *Perceived* Self-Location and *Perceived* Target Locations

It was also possible that during the test phase participants pointed or walked to where they perceived the target locations to be based on their new location. Based on this, heading angle was assessed again by accounting not only for perceived location after the non-visual walk but also for the perceived locations of the targets. Another new ideal heading angle was calculated using the coordinates of participants' drawn targets and drawn location at the novel location. Heading angle was then calculated by subtracting the response angle from the new ideal angle.

RESULTS

BASELINE FINDINGS

Did participants in the non-vision group perform better than chance at baseline?

Based on the method by which participants were taught the object names and locations during the learning phase, there was a question about whether participants' performance was better than chance. Mathematically, the mean heading angle of a chance performance is 90 ° over N iterations (i.e. responses). Using participant's actual unsigned responses rather than pointing errors, the mean of the slopes of their responses was calculated. If participants' response headings were greater than chance, the mean of the group's slope would be significantly greater than a slope of zero. A one-sample t-test revealed that the mean of the slopes of heading responses was significantly different from a slope of zero or chance, t (23) = 13.17, $p < .001$. Thus the performance of the non-vision group at baseline was better than chance for each target location which suggests that the target location influenced responses.

Unsigned Pointing Error

At baseline the vision and non-vision groups were not yet separated into pointing and walking groups so a repeated measures ANOVA using target, group (vision and non-vision) and gender was performed. The analysis revealed an effect of group, F (1, 44) = 5.55, $p < .025$, the mean unsigned pointing error for the vision group (M = 8.03 °, SE = .664 °) was significantly lower than the non-vision group (M = 11.44 °, SE = .694 °). The analysis also revealed an effect of target, F (2, 94) = 6.00, $p < .001$.

Figure 16 shows that the left hemispace targets 1 and 2 generated the largest error and were not different from each other but differed significantly from targets 3, 4 and 5, which did not differ from each other.

Signed Pointing Error

An analysis of signed pointing error using the same variables revealed an effect of target, F (2, 95) = 31.37, p < .001. Figure 17 shows that for targets 1 and 2, which are in the *left* half of space, pointing errors are the greatest *and* participants are pointing to the left of these targets. However, for the targets at comparable angles in the *right* half of space (4, 5), participants generated less pointing error and pointed to the right of the targets.

Experiment 1 versus Experiment 4

To address whether obtaining information about multiple target locations rather than a single target location facilitated the building of a visual or non-visual representation of space, the mean heading errors of the vision and non-vision groups from experiments 1 and 4 were compared. Although the type of sensory input was the same for participants in the two groups of both experiments, response output was not. For the purposes of this comparison however, it was assumed that measures of pointing and walking would generate heading errors of the same magnitude.

A simple factorial ANOVA comparing the mean heading pointing errors produced at baseline by the vision group of the present experiment (M = 8.03 °, SE = 0.66 °) was significantly larger than the heading error of the vision group in experiment 1 (M = 3.24 °, SE = 0.40 °), F (1, 36) = 28.1, p < .001. This suggests that building a

Figure 16. (Experiment 4). Mean unsigned pointing error at baseline across targets. Error bars represent standard error.

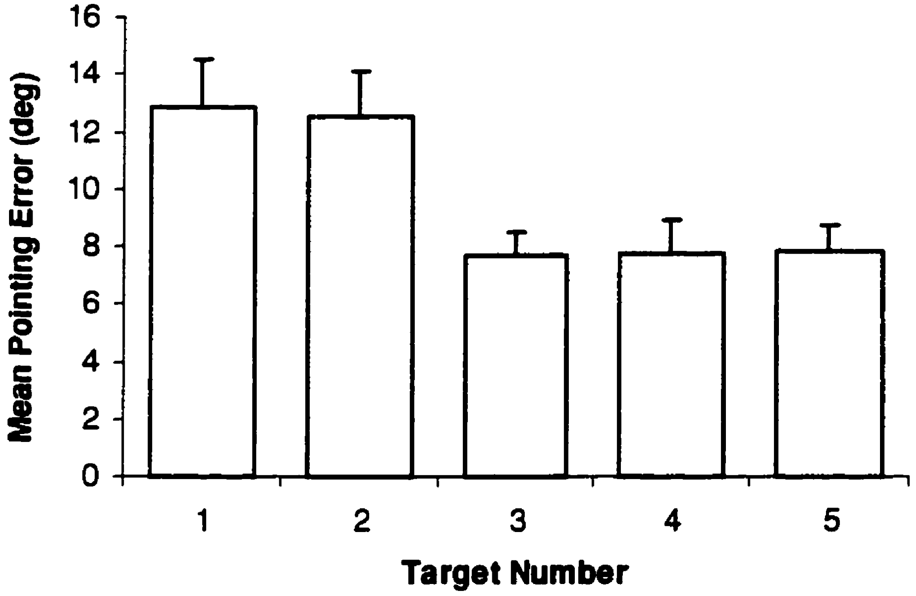
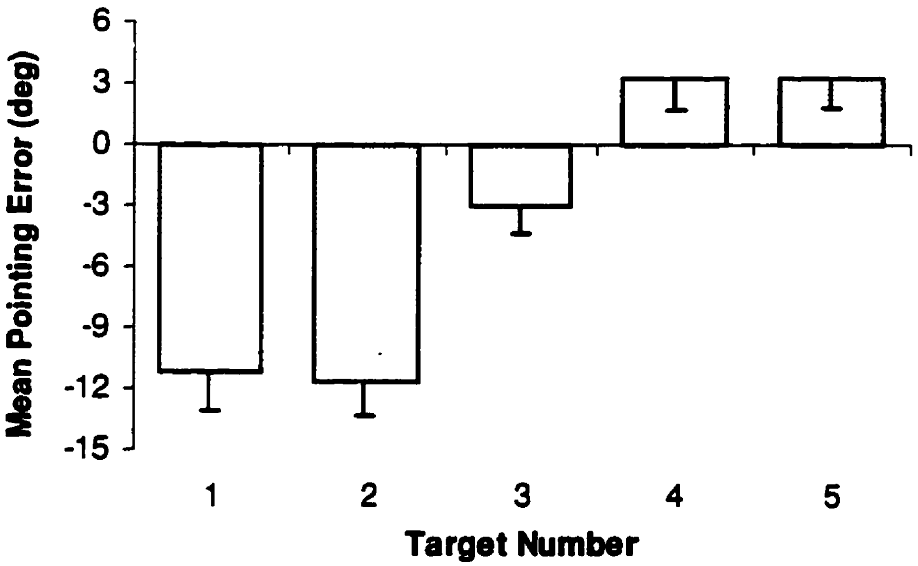


Figure 17. (Experiment 4). Mean signed pointing error at baseline across targets. Error bars represent standard error.



spatial representation of multiple targets was more challenging than encoding the location of a single object in space when vision was available. It is quite possible that the difference was the result of the differing response outputs; participants in experiment 1 walked while participants in experiment 4 pointed to indicate target location (see discussion). When individuals were asked to represent space without vision, multiple target locations did not make it more or less difficult to build that representation as the mean unsigned heading error of the non-vision group here (M = 11.44 °, SE = 1.28 °) did not differ from that of the non-vision group of experiment 1 (M = 9.21 °, SE = 1.05 °), F (1, 36) = 1.52, p > .1. The difference in memory load between experiment 1 and experiment 4 might also account for the differences between the mean heading errors produced in each experiment; participants were asked to remember the locations of 5 targets in the present experiment rather than a single target as in experiment 1. Therefore, it is also possible that participants were occasionally pointing quite accurately, but to the wrong target.

TEST FINDINGS

Although each participant experienced the same blindfolded walk from the starting position to the novel location, half the participants learned the locations of objects with vision and half without vision. These groups were further divided for the test phase: Half the participants from each group were randomly placed into either the pointing group or the walking group.

POINTING HEADING ERRORS

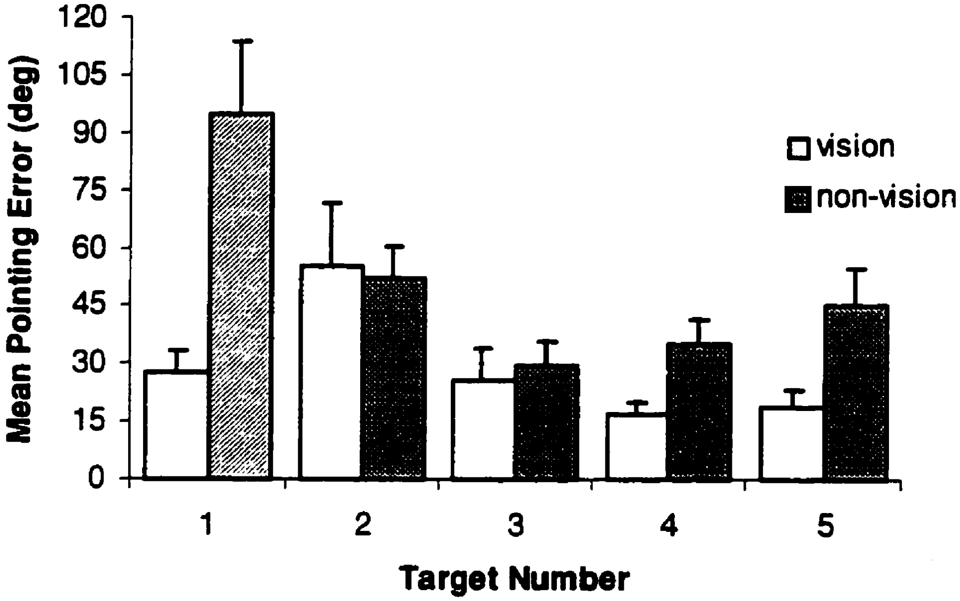
Unsigned

Vision Pointing Group vs. Non-Vision Pointing Group

Recall that the goal of the test was to examine the integrity of participants' representations after being led to a new location without vision. The errors produced from the test location are indicative of an individual's ability to re-map their representations of the target locations to fit with their new position in the court. There was a significant effect of target, $F(2, 33) = 6.25$, $p < .001$ and of group, $F(1, 20) = 6.81$, $p < .025$ but a target by group interaction qualified these main effects, $F(2, 33) = 4.50$, $p < .005$. Post-hoc simple effects analyses of the interaction revealed that the non-vision group produced significantly more pointing error for targets 1 ($p < .001$) and 5 ($p < .025$) from the novel location (see Figure 18).

The main effect of group is also important to discuss here because differences between the vision and non-vision groups were expected and the means may be compared to those found by Rieser et al. (1986). When asked to point from the novel location, the mean unsigned pointing error for participants in the vision group was 29.05 ° (SE = 5.6 °) and for the non-vision group was 51.53 ° (SE = 6.0 °); the vision group seems to have benefited from prior vision of the target locations. When Rieser et al. (1986) tested early blind, late-blind and blindfolded sighted participants on a similar task, they found similar unsigned mean errors: 49.6 °, 28.1 ° and 32.2 °, respectively. Pointing errors found by Loomis et al. (1993) were slightly lower than those found by Rieser's group; 38.4 ° for blind individuals and 31.4 ° for blindfolded sighted

Figure 18. (Experiment 4). Comparing the vision pointing and non-vision pointing groups on mean unsigned pointing error at test for each target. Error bars represent standard errors.



individuals. Even though participants in the non-vision group of the present experiment generated more error, the numbers from both studies are comparable. The discrepancy may be due to methodological differences.

Signed

Vision Pointing Group vs. Non-Vision Pointing Group

Signed data provide information about the direction of the errors. Similar to the unsigned findings, there was a main effect of the repeated factor, target, F (2, 46) = 4.67, $p < .01$ but the effect appears to be driven by the fact that, compared to all other targets, pointing errors for target 2 were significantly biased to the right. There was also an effect of group, F (1, 20) = 5.98, $p < .025$, indicating that the pointing errors are significantly larger and farther to the left of ideal for the non-vision group (M = -32.42°, SE = 11.86°) than the vision group (M = -0.456 °, SE = 4.6 °).

WALKED HEADING ERRORS

Were participants' walked heading errors better than chance for target 4?

Recall that to circumvent additional veering that may be caused by the directional bias of a target, all participants in the walking group at test walked to the book which was located directly in front of them. To show that participants had some idea of the direction of target 4 from the new location, their performance was compared to chance. If performance was not better than chance, it would suggest either that participants did not have a good representation of the target locations from the novel location or that they could not accurately update their own position and the locations of the target in order to walk to the book. Twenty-four random numbers were generated to represent random or chance responses. Using a simple F-test (Howell, 1996) that examined the difference between two sample variances it was revealed that the variance generated by the random responses was more than 4 times larger than the variance generated by the responses of participants. If the ratio of the larger (random numbers) to the smaller (participants' responses) variance is greater than 4.0, heterogeneity of variance can be concluded. In this instance, such a result suggests that the responses of participants clustered around the ideal target location more than they were random and indicates that participants had some idea of the direction of target 4 from the novel location.

Unsigned

Vision Walking Group vs. Non-Vision Walking Group

There was no significant difference in walked heading error between the vision (M = 20.45 °, SE = 6.0°) and non-vision (M = 17.56 °, SE = 4.9°) walking groups, F (1, 20) < 1.0. This suggests that, when attempting to walk towards the target object from the novel location, it did not matter whether participants learned the object locations visually or non-visually.

Signed

Vision Walking Group vs. Non-Vision Walking Group

No signed heading effects reached significance. Inspection of the data show that both groups veered to the left of the target but that the vision group (M = - 4.7 °, SE =

7.36 °) veered slightly more than the non-vision group (M = - 2.35 °, SE = 7.16°). Also, males (M = - 6.1 °, SE = 6.28 °) veered more to the left than females (M = - 0.98 °, SE = 8.07°). This latter finding is reminiscent of the findings from experiment 1 where males veered considerably more to the left during an unguided blindfolded walk.

WALKED DISTANCE ERRORS

Were participants' walked distance responses better than chance for target 4?

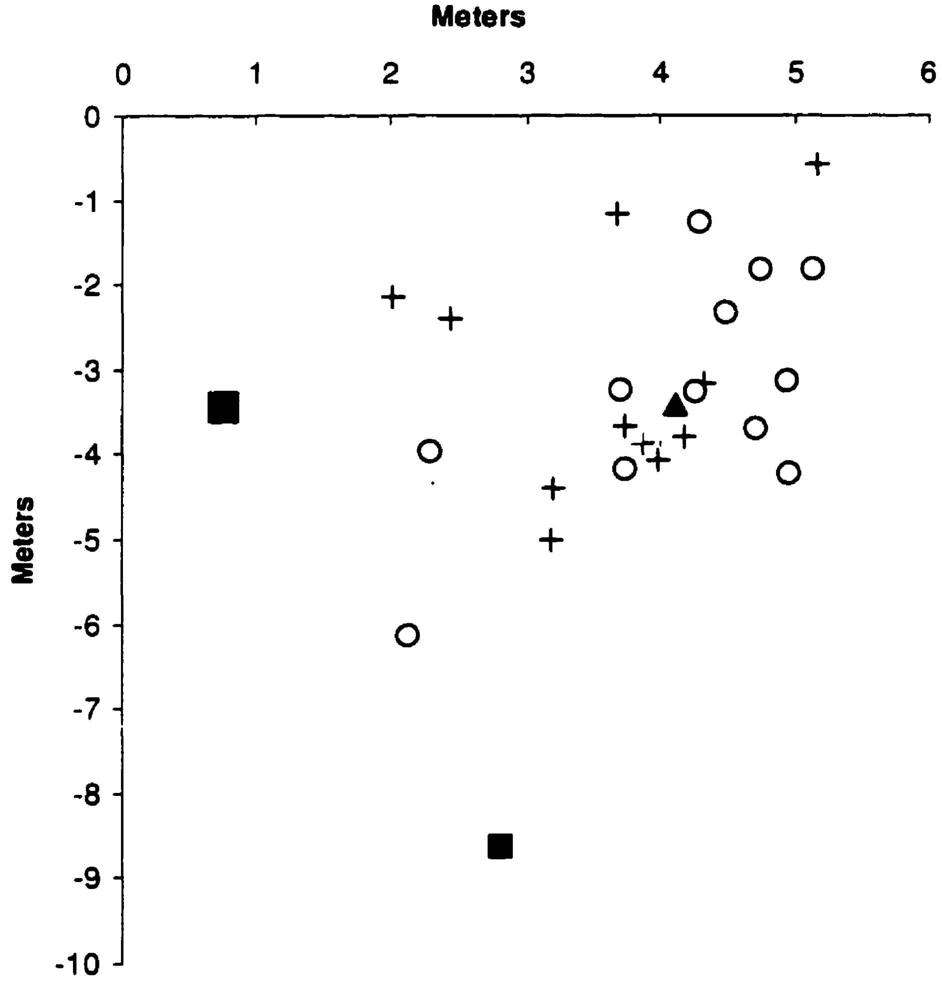
Participants' estimates of the distance to target 4, which was 4.1 m from the new location, were tested against chance performance. The mean unsigned walked distance that would be obtained by chance was 2.44 m, halfway between the feet and the wall of the court. The *obtained* mean unsigned walked distance response for the vision group was 3.17 m (SE = 0.25 m) and the non-vision group was 3.64 m (SE = 0.24 m). One sample t-tests showed that these means were statistically different from chance performance. This finding suggests that participants' estimates of the distance to target 4 the novel location were as good as their estimates of its direction.

Unsigned

Vision Walking Group vs. Non-Vision Walking Group

No effects were found for mean walked distance error but inspecting the means indicates that the vision group (M = 0.609 m, SE = .184 m) was slightly more accurate than the non-vision group (M = 0.735 m, SE = .131 m) (see Figure 19).

Figure 19. (Experiment 4). Scatterplot of actual walked responses to target 4 from the novel location. Crosses represent individuals from the vision-walking group and the open circles represent individuals from the non-vision walking group. The solid triangle indicates the location of target 4, the small square the starting point and the large square the novel location. The abscissa represents the width of the court and the ordinate represents the length of the court.



Signed

Vision Walking Group vs. Non-Vision Walking Group

A simple ANOVA on group and gender for mean signed walked distance error revealed an effect of gender, F (1, 20) = 9.74, p < .01. Unexpectedly, males (M = 0.524 m, SE = .184 m) overestimated the target while females (M = - 0.42 m, SE = .178 m) slightly underestimated the target's distance. No other effects reached significance.

Pointing Angle vs. Walked Heading to Target 4: A Comparison of Response Outputs

Researchers have used pointing accuracy to examine the perception of heading or direction after non-visual locomotion (e.g. Rieser et al. 1986; Loomis et al. 1993). We questioned whether pointing to a previously learned target was more or less accurate than walking to the same target location, especially when participants were in a location other than where target locations were originally learned. One goal of this experiment was to compare the accuracy of pointing and walking to a previously learned target in order to assess which was a better index of heading estimation. It was hypothesized that because locomotion was likely the type of response output one would utilize to navigate within the real world, indicating the location of a previously learned target by walking to it without vision might be more accurate than indicating its spatial location by non-visual pointing. If prior vision of the target locations were available there would be no difference between the heading errors produced by pointing and walking.

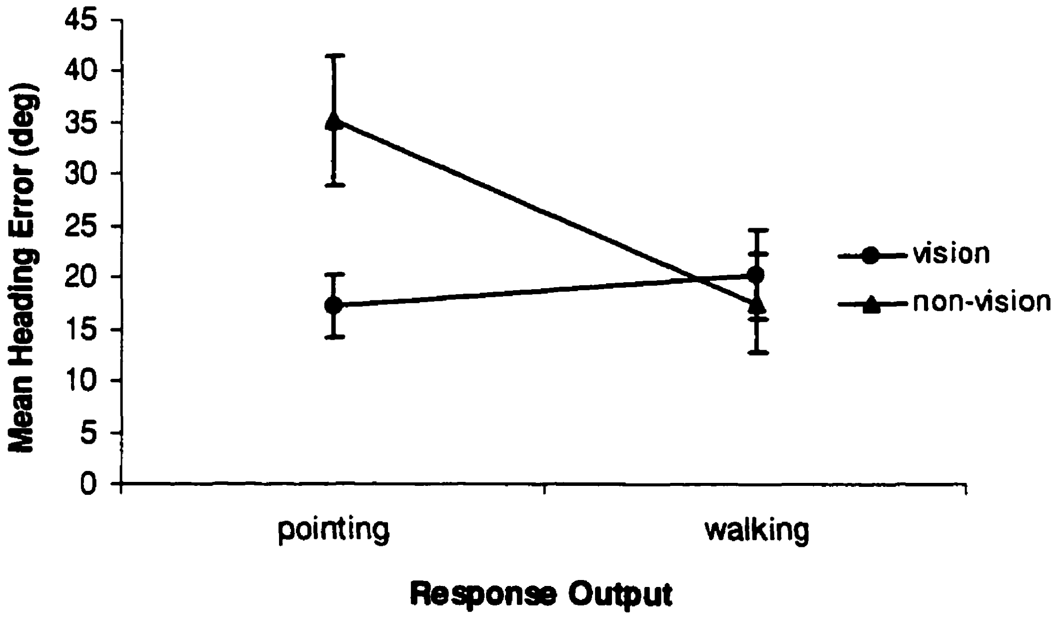
Unsigned Errors

An ANOVA was conducted on group (vision or non-vision), response output (pointing or walking) and gender for target 4. No main effect was significant but there was an interaction between response output and group, F (1, 40) = 4.68, $p < .05$. Detailed post-hoc simple effects analyses showed that heading error for pointing was significantly higher than walked heading error for the non-vision group, F (1, 40) = 6.68, $p < .025$. And, as predicted, the heading error for pointing and walking did not differ for participants who received visual information (see Table 4). The vision pointing group also produced significantly less pointing error than the non-vision pointing group, F (1, 40) = 6.95, $p < .025$ (see Figure 20).

Signed Errors

An analysis of signed errors for variables response output, group and gender revealed an effect of response output, F (1, 40) = 9.75, $p < .005$; pointing in the direction of target 4 produced significantly more heading error (M = - 20.13 °, SE = 5.24 °) than walking (M = 1.21 °, SE = 5.07 °) to the same target. There was also a significant group by gender interaction, F (1, 40) = 7.66, $p < .01$. Post hoc simple effects analyses indicated that males in the non-vision group (M = -25.16 °, SE = 7.31 °) produced significantly larger heading errors (combined pointing and walking heading errors) to the left of the target than females (M = -4.58 °, SE = 9.57 °), F (1, 40) = 4.53, $p < .05$. In contrast, the responses of males (M = 4.57 °, SE = 6.03 °) and females (M = -12.69 °, SE = 6.24 °) in the vision group did not differ. Further, males in the vision group produced less heading errors than males in the non-vision group F (1, 40) = 9.47, $p < .01$.

Figure 20. (Experiment 4). Mean unsigned heading errors generated by each group at each response output at target 4 at test. Error bars represent standard errors.



MAP FINDINGS

The x-y coordinates of drawn feet locations and drawn target locations were extracted from each participant's map. These coordinates were then converted from map units (cm) to real-life units (m) and were compared to the locations of the real novel feet and the real target locations. Only unsigned errors were reported as these provided a good general measure of participant's responses. For clarity, the data from the maps will be referred to as 'drawn' but the reader is to keep in mind that that which was drawn on the map represented participant's perceived self and target locations.

Perceived Novel Location

All participants were led without vision to the novel location. Evaluating the accuracy with which participants perceived this non-visual walk, might provide more information about the nature of their pointing and walking errors. The mean perceived location of the novel feet drawn by participants in the vision groups and non-vision groups was compared. The only significant effect for this analysis was for group, F (1, 44) = 16.03, $p < .001$. By inspecting the group means it was noted that the vision group perceived that they walked farther than they actually had, their walked distance, as calculated from the maps, was 6.53 m (SE = .175). On the other hand, the non-vision group was more accurate in their perception of their new location but they perceived that they walked just short of the target, their mean walked distance was 5.37 m (SE = .222) (see Figure 21). The real distance from the starting point to the novel feet was 5.59 m.

Drawn Feet-Real Targets

Would pointing and walking errors decrease if we accounted for their perceived position at the time of response at test? For this analysis we used the drawn feet coordinates (which represented where participants perceived themselves to be prior to responding) and the real target locations and calculated a new ideal angle to which their responses was compared. Separate ANOVAs were run on each of the four groups.

Results from a repeated measures ANOVA indicated that, overall, there was no significant decrease in heading error (either pointing or walking) for any group when perceived position at the novel location was taken into account. The only significant results were an effect of target for both the vision pointing group, $F(1, 30) = 6.31$, $p < .001$ and the non-vision pointing group, $F(2, 35) = 13.67$, $p < .001$. This effect represents the strong influence that target laterality has on pointing error and was primarily driven by the fact that target 2 produced the largest heading error in both groups. Accounting for perceived location after the non-visual walk to the novel feet did not appear to explain the increase in unsigned heading errors at test.

Drawn Feet-Drawn Targets

During the experimental sessions it was observed that participants may have pointed or walked to targets based not only on where they perceived themselves to be but also where they perceived the targets to have been in relation to their perceived location. It was reasonable for us to ask whether unsigned heading errors might decrease if we accounted for both the perceived self-location at the novel feet and the perceived target locations from this new position. In this instance we tailored the calculations of pointing errors to each participants' map and calculated new ideal angles to targets using participants' drawn feet and drawn target locations. Separate ANOVAs were run on each of the four groups.

When responses were compared to newly calculated ideals that were based entirely on information from maps, the only significant effect was an interaction between target and map condition (i.e. original response errors or errors based on maps) for the non-vision pointing group only, $F(2, 46) = 4.05$, $p < .05$. Figure 22 shows that, for all targets but target 3, heading errors decrease when the perceived self and target locations were accounted for.

Figure 21. (Experiment 4). Scatterplot of individuals' perceived position (as extracted from their drawn maps) at the novel location after the non-visual walk. Circles represent individuals from the non-vision group. Triangles represent individuals from the vision group. Ex's mark each target location. Solid square is the starting point and the open square is the novel location.

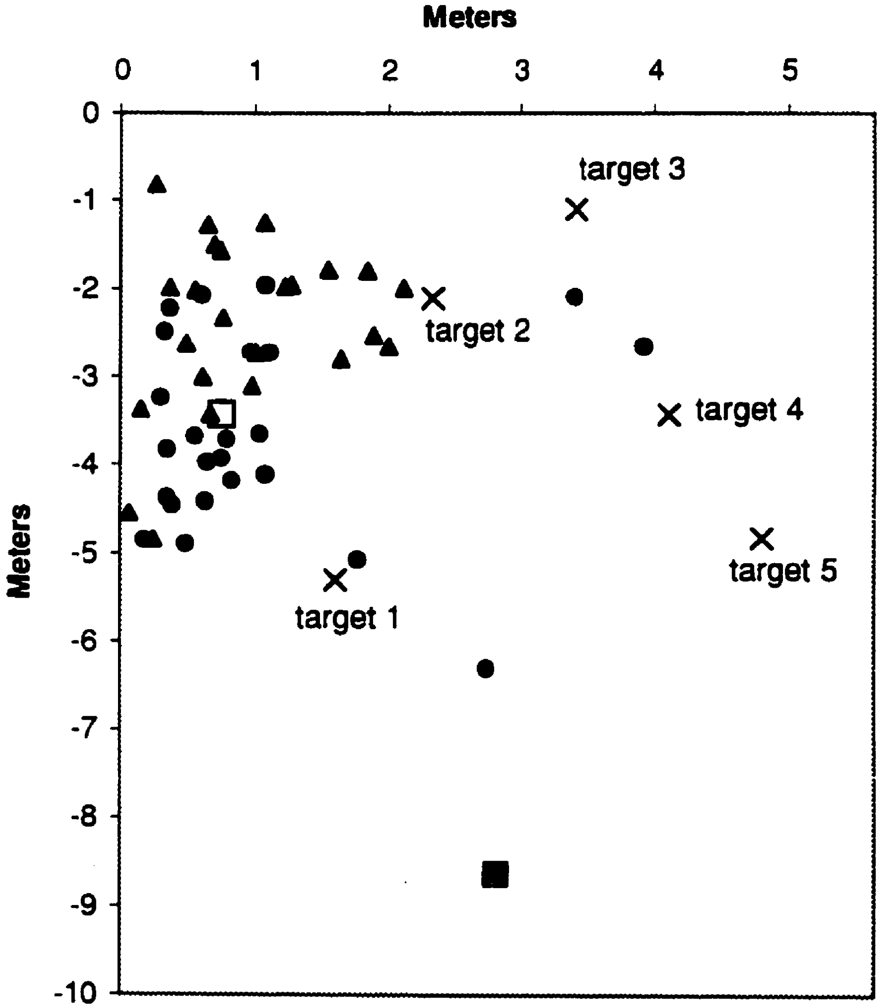
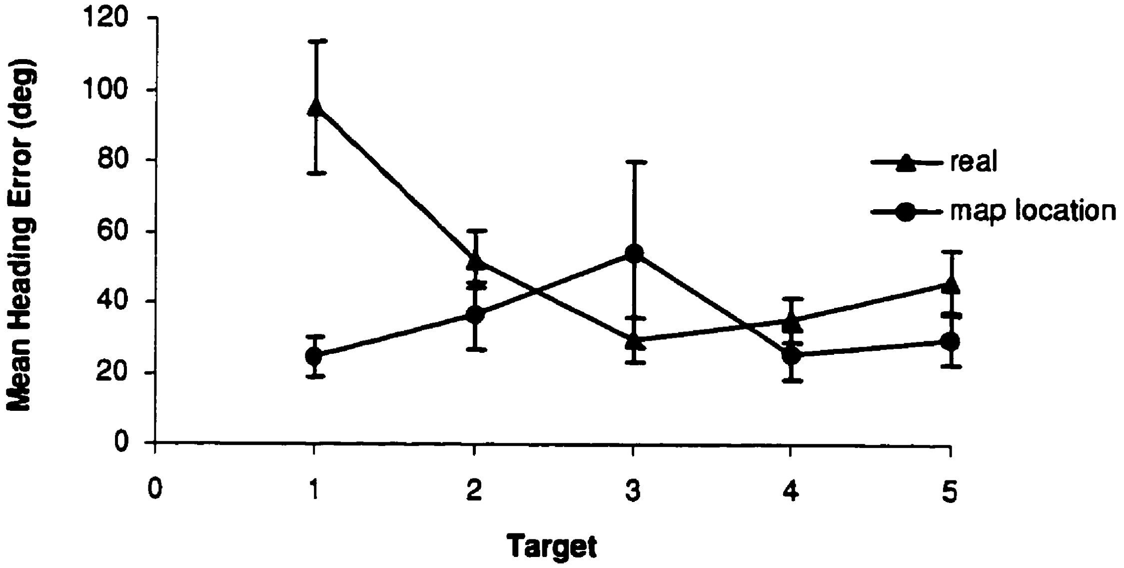


Figure 22. (Experiment 4). Comparing original unsigned heading errors with the unsigned heading errors generated by accounting for participants' perceived location at the novel feet and their perceived target locations using drawn maps. Error bars represent standard errors.



DISCUSSION

Building a representation of multiple target locations in space was only slightly more difficult than learning the location of a single target when vision was available but no more difficult when the locations of those targets were learned without vision. When baseline responses were examined participants who were required to visually represent the locations of five different objects generated slightly larger heading errors than participants in the vision group of experiment 1 who were asked to view only a single target location. In contrast, the added spatial information provided by multiple target locations neither increased nor decreased performance accuracy when target locations were learned without vision. These findings indicate that although non-visual performance is never as accurate as performance with prior visual information, it is still possible to build a relatively accurate spatial map of multiple object locations without vision. These results also support the idea that prior visual information facilitates subsequent non-visual performance because when participants were allowed to learn the locations of the objects with vision, they generated less error than those participants who were taught the locations of the objects without vision. That prior vision facilitates accurate non-visual performance is a very robust finding and has been found by others (e.g. Loomis et al. 1992; Takei et al. 1997; Thomson, 1980; Steenhuis and Goodale, 1988; Glasauer et al. 1994)

Despite some methodological differences, the results of this study replicate those found by Rieser et al. (1986) and Loomis et al. (1993). For the baseline condition, the pointing heading errors generated by participants in the vision and non-vision groups of present experiment were very similar to those generated by Rieser's blindfolded sighted group although the errors produced by our participants were lower. The lower pointing errors produced by participants in the present study may be a reflection of the fact that participants used a hand-held laser pointer rather than a pointer mounted on a protractor that had to be manipulated with the hand (Rieser et al. 1986).

The relatively accurate baseline performance suggests that efference copy, vestibular and proprioceptive sensory information derived from non-visual locomotion provided sufficient information to allow participants in the non-visual group to build a spatial representation of the target locations. Also, even though target locations were tested randomly, making it necessary to actually encode the objects' spatial locations rather than rely on the memory of their names and order, performance was still quite good. However, the pointing errors produced in this experiment were slightly larger than errors produced by individuals in experiment 1 who walked without vision to the target locations after learning them without vision. Comparing the results from these two experiments (in which targets were at comparable locations) suggests that pointing and walking are not comparable response outputs (see below).

The results of the test phase of the present study also replicated the findings of Rieser et al. (1986) and Loomis et al. (1993). When participants were led without vision to an unknown location and were asked to point towards previously learned targets, those that received prior visual information about the target locations pointed with more accuracy than did individuals that learned the target locations without vision. This further shows how strong an influence prior visual information has on non-visual performance. One reason that prior visual information leads to better performance may be that visual representations endure longer than non-visual sensory representations of space. However, for this to be used as an explanation of the difference between the groups, the characteristics of the non-visual sensory trace (i.e. how quickly it decays, how long it takes to form) must be studied empirically. Nonetheless, it is obvious that prior visual information is crucial for accurate non-visual pointing performance.

The Effect of Target Location: Laterality and Eccentricity

One consistent finding in the present experiment was that the locations of certain targets were more difficult to accurately point towards than were others. This may be the result of target laterality. At baseline, pointing accuracy to targets in right hemispace was often greater than for left hemispace targets. The pointing errors produced by targets 1 and 2, both located on the left side of the court, were of similar magnitude but were 5 ° larger than errors for other targets. Others have also found effects of target laterality on motoric localization tasks (e.g. Fisk and Goodale, 1985; Goodale and Fisk, 1984; Haber et al., 1993). Fisk and Goodale (1985) studied reaching/pointing accuracy to briefly flashed targets that fell either to the right or left of a central fixation point on a screen. They found that when participants had to reach out to point to the contralateral space to indicate the position of a target their errors were larger than for ipsilateral targets.

Target eccentricity has also been shown to influence the accuracy of reaching/pointing responses. Fisk and Goodale (1985) also found that target eccentricity influenced the accuracy of their participants' responses; error increased with increasing target eccentricity. Haber et al. (1993), who studied nine different pointing methods for indicating the direction of object locations, found that targets far to the left or right of

90 ° produced larger pointing errors in blind participants. Although the lack of target eccentricity could have influenced the responses to target 1, for which the largest errors were recorded, it was at approximately the same eccentricity as target 5 which was ipsilateral to the pointing arm. Thus, it seems more likely that the laterality of the targets better explains the large pointing error at targets 1 and 2.

From the novel location, target 1 produced the largest pointing error even though it was located in the right half of space. It is possible that the reason it was so difficult for the majority of participants to correctly indicate the location of target 1 was because it was positioned along the path from the starting point to the novel location. After the experiment, many participants reported that they thought the non-visual walk to the novel location ended before they would have arrived at target 1. As a result participants pointed to this target as if it was behind them and to their left when at the novel feet. This led to pointing errors that were often larger than 100 degrees.

Heading Errors are Dependent on Response Output and Visual Input

It was hypothesized that when participants were asked to point without vision to a previously learned target location their heading errors would be different than if they were asked to walk without vision to the same target. It was also predicted that performance using these two types of responses would vary based on whether the target locations were learned visually or non-visually. As predicted we found that pointing produced heading errors of different magnitude than walking but unexpectedly we found that a walking response afforded a more accurate estimation of the distance and the direction towards a previously learned target than a pointing response did. It was also found that, in comparison to having prior visual information about a target's location, learning the same target location without vision significantly affected pointing responses but not walking responses. Thus, the internally generated non-visual spatial representations were sufficient to enable individuals to walk but not to point to target locations from a novel location.

Many, but not all, of the experiments conducted in the area of non-visual human navigation utilize non-visual locomotion as a response measure. Non-visual walking appears to be the most appropriate response with which to measure navigation-related behaviour as what is being measured invariably involves path integration, the basis of non-visual navigation. However, some studies in this area (e.g. Loomis et al. 1992, 1997; Rieser et al. 1986; Rieser, 1989) do not appear to regard the nature of the response as particularly important. That is, when assessing how well an individual can estimate, for instance, the egocentric location of a previously viewed target, it would not matter whether the targets' location was indicated by pointing to it or by walking towards it; the two response measures are assumed to be similar. The findings of the present study revealed that pointing might be a less accurate measure of an individual's representation of space than walking because its accuracy as a response is dependent on prior visual input. Thus pointing might not be the best measure of non-visual space representation.

Why Did Heading Errors Increase from Baseline to Test?

What was interesting about the responses at the test phase was not only that the vision and non-vision groups differed but that the errors increased from baseline to test.

The vision group increased their error from 8 ° at baseline to 17 ° (pointing) and 20 ° (walking) at test (i.e. TL 4) and the errors produced by the non-vision group increased from 11 ° to 35 ° (pointing) and 17° (walking). We were curious as to what brought about this increase. Results indicated that heading responses at baseline and at test were not random as participants had some kind of representation of the target locations in both conditions. Accounting for potential perceptual error of self and object position after the non-visual walk using participants' drawn maps did not convincingly explain the increase in error from baseline to test. Although participants were able to mark their updated locations on the maps fairly accurately, there was little or no relation between the locations that they indicated on the maps and either their pointing or walking responses at test. Even when we accounted for where participants thought they had been standing and where they thought the targets had been, there was no evidence that these perceptions had any influence on their responses. In trying to describe the patterns of errors produced by his participants at test, Rieser et al. (1986) attempted to identify whether participants, when at the novel location, pointed to the targets from a point of observation *other than* where they were led. He characterized three types of responses. 'Response learners' were individuals who would produce the responses learned at baseline. 'Rotators' would generate responses from the novel location that would only account for the rotation in heading but not for the translation (i.e. distance) of the walk and 'translators' would account for the translation but not the rotation in heading of the walk. A computer program simulated the pattern of responses for each target based on these characterizations and evaluated them against participants' real response angles. According to these criteria, participants rarely responded randomly and the majority of participants responded as if they were "...standing in the neighbourhood of the actual novel point of observation." (Rieser et al. 1986, p. 185). Overall, he found that the rotation in heading was better compensated for than the translation of the walk to the new location. In a way, the maps we employed in the present experiment addressed the same problem that Rieser's computer simulation did. Because we suspected that participants responded based on their perceived location and perhaps the perceived target locations as well, we analyzed their drawn maps. Unfortunately, the maps were not particularly helpful in explaining participants pointing and walking responses at test. Indeed, the utility of the maps may be called into question. First, participants were allowed to remain in the court while they drew the objects and the novel location. This may have led to some kind of cognitive influence on the internally generated representation of the distances and angles between the objects and the novel location. Second, the map templates were not originally drawn to scale and this may have affected the perceptual-to-map transformations that occur when putting to paper what one has experienced through locomotion. However, although these problems existed, a more important issue underlies the utility of the maps. We believe that the process used to draw the maps was not the same as the process used to point or walk to the targets. This suggests that there may not be a single representation of space that may be used by different response outputs, whether that output is a drawing response, a verbal response or a walking response. Navigational tasks, such as those employed here, do not all draw from the same "map in the head". Instead, different response outputs quite possibly make use of different representations. Similarly, the reason for the increase in heading error from baseline to test for the non-vision pointing group is not the same as the explanation for the walking groups. The large error seen in the non-vision-pointing group at test as compared to the vision-pointing group at test may be related to the privileged connection between vision and the arm-hand motor system. It seems that we are predisposed to have our eyes and head oriented in the same direction when we are pointing or reaching towards an object in visual space. It has been found that congruent retinal and extra-retinal signals, which allow for the localization of a target in space, also give rise to directionally appropriate arm-hand motor responses like pointing (e.g. Enright, 1995; Bock, 1986). If the eyes and head are both oriented towards a target prior to pointing without vision to that target, extra-retinal or "efference copy" of eye position signals (as generated by the oculomotor system) supply the information that allows for delayed, direction-appropriate motor responses like pointing. If the eyes and head are not oriented to the target location at the time of acquisition of that target's spatial location, or if the orientation of the eyes and head are at odds, non-visual pointing responses are less accurate. It is possible that a lack of extra-retinal information and as well as lack of vision during the pointing response adversely affected the non-vision group's pointing performance. In a series of experiments Bock (1986) investigated the accuracy of non-visual pointing movements under different conditions of retinal and extra-retinal congruence. The first two experiments assessed whether retinal information alone was sufficient for localization of the target location with a pointing response. Participants foveated a fixation light (LED) projected on a cylindrical screen directly in front of them. Their heads were stabilized in the forward direction with the use of a bite bar and their eyes and head were thus oriented in the same direction. Visual targets were randomly presented at different locations within the central 50 ° of the visual field. After the target was presented, participants were required to point to the location of the light *without vision of their arm and without moving their eyes*. Results indicated that non-visual pointing was not accurate; participants pointed too far to the right for right hemispace targets and too far to the left for left hemispace targets. Similar results were found in the second experiment when eye position was manipulated during target presentation and head position remained straight ahead. In a third experiment Bock examined whether extra-retinal signals alone provided enough information for accurate target localization through pointing. Participants were asked to "look" at an imaginary target on the screen while in total darkness. Then, without moving their eyes from this imagined target, they were to point towards it. Results indicated that, even though the eyes were oriented in the direction of the imagined targets, pointing was inaccurate. Bock's experiments suggest that mapping the visual surround using either the peripheral retina alone or extra-retinal signals alone is not sufficient for target localization using an arm movement. He concluded that it is likely the interaction of the retinal and extra-retinal signals that shapes the internal representation of space for a pointing movement. Enright (1995) also examined the impact of eye orientation on delayed non-visual pointing. In one condition participants were required to keep their eyes and head aimed at a central fixation light that was displayed on a panel in front of them while a target light was presented to the periphery. Immediately after the light was extinguished they were to maintain their eyes and head in the same position and point to the remembered target location. In another condition participants were allowed to make rapid eye movements towards the remembered target location after it was extinguished and were to hold fixation at this location while pointing towards it. He found larger pointing errors were produced when participants were forced to maintain their eyes and head on the central fixation point while pointing towards the remembered target location. Significantly less pointing errors were found when participants were allowed to orient their eyes towards the target location even though the target had extinguished and the pointing movements were in total darkness. The data of the present experiment support the theory that a pointing response is yoked with congruent retinal stimulation <u>and</u> eye-head position at the time of target acquisition; participants who encoded target location both retinally and extra-retinally (vision pointing group) made very little error. Also, results from Bock's (1986) imagined target experiment suggest that even though you can't see a target, having your eyes oriented in its direction can help you to point with some accuracy to that target may explain why the vision pointing group did relatively well and why the non-vision pointing group performed poorly but does not explain why the errors of the two walking groups increased at test. Because learning the location of a target without vision did not adversely affect the accuracy of participants' walked heading from the novel location, we propose that vision and locomotion are not as tightly coupled as vision and pointing. Experiment 5 served to address this issue.

EXPERIMENT 5

Based on the results of experiment 4, the two response outputs, pointing and walking, produced different results depending on whether vision was available or not at the time that target locations were learned. Specifically, we found that if the location of a target was learned non-visually, the accuracy with which an individual could point without vision to that target location from a novel location decreased. In contrast, walking to that same target produced much less error. Further, when a target was learned with vision, there was no difference in the amount of error produced by pointing or walking to that target from a novel location. The theory put forth in the discussion of the previous experiment suggested that fixating a target with the eyes *and* the head facilitates non-visual pointing accuracy (Enright, 1995; Bock, 1986). Forced central fixation during the visual acquisition of a target's spatial location, which provides retinal information but prevents the acquisition of efference copy information, affects accurate encoding of its location and decreases subsequent non-visual pointing accuracy (Enright, 1995). Based on this previous research, experiment 5 was conducted to test the hypothesis that a pointing response is yoked with retinal and extra-retinal (eye-head orientation) input at the time of target acquisition but that vision and locomotion are <u>not</u> as tightly coupled. By forcing participants to stare at a distant central fixation point (which allows for retinal stimulation but prevents extra-retinal or efference copy information) it was hoped that the accuracy with which participants could encode the locations of objects and subsequently point to these objects without vision would be reduced. This experiment also served as a replication of experiment 4.

We used the same methods and procedures as in experiment 4 but some minor modifications had to be made in order to allow us to manipulate extra-retinal cues during the acquisition of a target's spatial location. We predicted that fixating on a central target while trying to learn the spatial locations of objects would increase the unsigned pointing error at baseline for the vision group as compared to previous baseline performance where both retinal and extra-retinal information was available. Because participants in the non-vision group were led without vision to and from the target locations, we predicted that forced central fixation during this learning phase would not increase the unsigned pointing error produced by this group at baseline. At test, the unsigned heading error of the vision pointers was predicted to approach the mean heading error of the non-vision pointers because central fixation has removed that which made the vision group in the previous experiment so accurate at test: Extra-retinal information about target location. For the two walking groups, it was predicted that their unsigned heading errors might increase slightly from those seen at test in experiment 4 but would not differ statistically. If these predictions were supported, this experiment would provide strong support for the idea that locomotion is not as tightly coupled to vision as is pointing.

METHODS

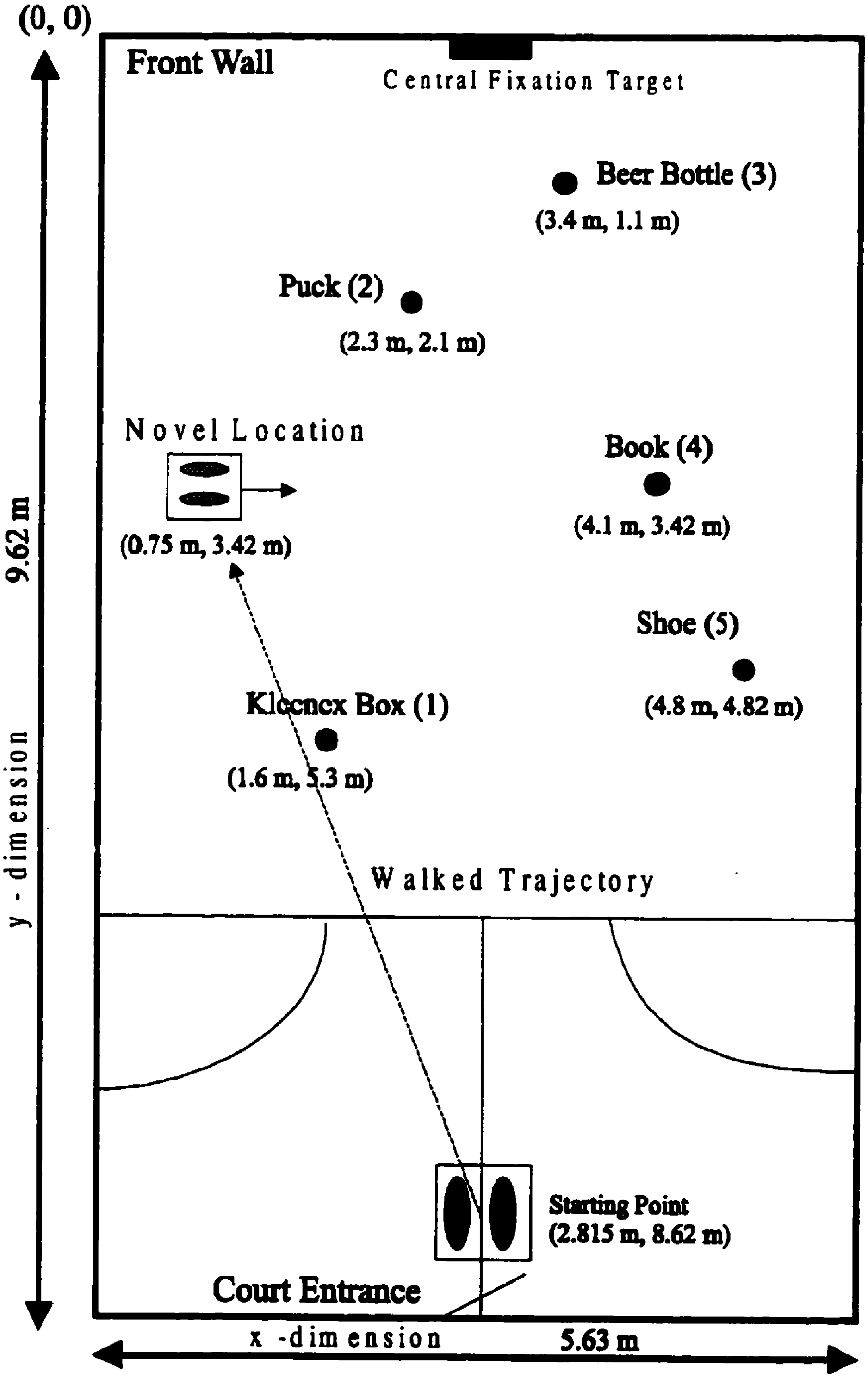
Participants

Forty-eight right-handed participants (24 males and 24 females) participated in this study. All participants were paid undergraduate volunteers from the University of Waterloo.

Apparatus

All trials took place in the same squash court used in previous experiments. Like previous experiments, the starting point and the novel location were indicated by raised foot impressions fastened to the floor of the court. Because fixation of the targets was not permitted in this experiment and the locations of small, low contrast objects were difficult to encode with the periphery, the arrangement of objects differed slightly from the previous experiment and one object was substituted for one with better contrast (Figure 23). A fluorescent hockey puck, a shoe, a beer bottle, a book and a Kleenex box, represented the five target objects. As in the previous experiment, all objects, except for object 4, the book, were randomly located at different locations on the floor of the court and could be easily viewed and recognized from the starting position. All participants pointed to the locations of objects using a hand-held laser pointer. Protective earphones dampened auditory information and the blindfold for all responses was a set of darkened lab goggles. Affixed to the front wall of the court at eye level (1.94 m from ground) was the central fixation target: A white board (0.56 m wide x 0.71 m long) with 5 rows of 5 numbers printed in black ink. Each number was 6 cm wide and 10 cm high. To prevent participants in the non-vision group from using extra-retinal signals to aid object localization, they were asked to fixate and read the numbers from the board while they were being led to each target location. This had the effect of making head and body orientation incongruent as the head was oriented in the direction of the fixation target while the body was oriented in the walking direction. To limit the amount of vision received while reading the numbers, participants wore a pair of modified swim goggles that allowed only 1.5 ° of visual angle when standing at the starting location. Each eyepiece of the goggles was extended 3.5 cm and a single pinhole was made in each modified eyepiece. All that could be seen through the goggles

Figure 23. (Experiment 5). Scaled bird's-eye view of the court dimensions, the location of the starting point (baseline position) and the novel location (test position) and 5 targets for experiment 5. Note that all that has changed are the objects at targets 1, 2 and 5 experiment 4.



from the starting location was the fixation target and approximately 30 cm of white wall on either side of the board.

BASELINE

Procedure: Target Acquisition

Vision Group

In the previous experiment participants in this group were allowed to turn their head and eyes toward each target in order to encode its spatial location. In the present experiment, participants were asked not to turn either their head or their eyes in the direction of a target while encoding its location. Instead, they were asked to fixate on the central fixation target that was affixed to the front wall of the court. For the initial learning session, participants read the first 2 rows of numbers aloud at a rate of one per second, while at the same time trying their best to remember the locations of the objects on the floor. This was to make sure that participants were not looking at the object locations directly but were fixating straight ahead. Prior to viewing the spatial layout of the five target objects, participants memorized the names and spatial order of the objects. After the first two rows of numbers were read, (about 10-12 seconds), participants were blindfolded and asked to point in the direction of the objects that were named at random. After these baseline responses were recorded, participants were given a final opportunity to encode the spatial location of the objects on the floor by fixating the distant board in front of them and reading the last three rows of numbers. The participants were then blindfolded, the targets were removed from the floor of the court and they were guided without vision to a novel location in the court.

Non-Vision Group

Similar to the vision group, participants in the non-vision group memorized the names and the spatial order of the target objects. Because vision of the target locations was not allowed, the locations of the objects were learned by guiding blindfolded participants to and from the location of each object in the order that they were memorized. In the previous experiment participants in this group were able to have their head oriented in the direction of the walk, which was akin to having their head and eyes oriented to the target location. However, because we were interested in performance accuracy without efference copy signals from the eyes and head, participants were asked to fixate, through a small hole in each eye of a pair of darkened goggles, the central target affixed to the front wall of the court. They were asked not to move their eyes from this board during the outbound journey to the target locations. To ensure that participants were fixating the board through the small holes, they were asked, while being led to the target, to recite the numbers on the board aloud. On the way back to the starting position participants were asked to close their eyes to ensure that no other visual information was available about their path. After all target locations were learned once, participants were blindfolded completely and asked to point, without vision, in the direction of a target named at random. Before being guided without vision to the novel location for the test trials, participants were led out to the targets one additional time.

TEST

Vision Walking & Pointing

Participants in the vision group were further divided at test: Half of the participants were asked to walk to target 4 while the other half were asked to point to all the targets named at random from the novel location.

Non-Vision Walking & Pointing

Participants in the non-vision group were further divided at test: Half of the participants from the non-vision group were asked to walk to target 4 while the other half were asked to point to all the targets named at random from the novel location.

All data were analyzed in the same manner as in experiment 4.

RESULTS

BASELINE FINDINGS

Did participants in the non-vision group perform better than chance at baseline?

In order to confirm that target locations influenced participants' pointing responses, we calculated the slopes of each individual's response at all target headings. Using participant's actual unsigned responses rather than pointing errors, the mean of the slopes of their responses was calculated. If participants' response headings were greater than chance, the mean of the group's slope would be significantly greater than a slope of zero. A one-sample t-test revealed that the mean of the slopes of heading responses was significantly different from a slope of zero or chance, $\underline{t}$ (23) = 16.35, $\underline{p} < .001$. This indicates that the performance of the non-vision group at baseline was better than chance and that pointing responses were towards the learned targets.

Unsigned Pointing Error

Because the groups were only distinguished as either vision or non-vision at baseline, a repeated measures ANOVA was performed on target, group (vision/non-vision) and gender. The analysis revealed an effect of target, $\underline{F}$ (3, 127) = 5.52, $\underline{p} < .001$ but no other effects reached significance. As with the non-fixation experiment (experiment 4), the largest pointing error was produced for targets 1 and 2, which were located in the left half of space. The pointing error produced at these two targets differed significantly from the other targets, which did not differ (see Figure 24).

Signed Pointing Error

A repeated measures ANOVA on the signed data for the same variables also revealed an effect of target, F (2, 93) = 19.4, $p < .001$. The effect of the target location was the same; targets in the left half of space generated the largest pointing error. Save for the error produced at targets 4 and 5, all participants pointed to the left of the actual target location. There was also an effect of group, F (1, 44) = 4.95, $p < .05$ where the responses of the vision group were affected by the forced-fixation more than the non-vision group as their pointing was biased more strongly to the left of the ideal target location. There were no significant interactions between the variables. Figure 25 shows the mean signed pointing errors at baseline for each group across targets.

TEST FINDINGS

POINTING HEADING ERRORS

Unsigned

Vision Pointing Group vs. Non-Vision Pointing Group

There was a significant effect of target, F (1, 25) = 15.96, $p < .001$. Of the five targets, target 1 (M_1 = 91.9 °, SE = 15.5 °) and 2 (M_2 = 41.0 °, SE = 4.38 °) generated the largest pointing error at test by the two groups (Figure 26). It was predicted that forced central fixation would increase the error produced by the vision group such that it would not be different from the non-vision group at test. This hypothesis was supported by a marginally significant effect of group, F (1, 20) = 4.29, $p = .051$. However, although these groups were barely different statistically, the vision group (M = 34.12°, SE = 4.35 °) still produced less pointing error than the non-vision group (M = 48.8 °, SE = 5.12 °).

Figure 24. (Experiment 5). Mean unsigned pointing error at baseline for each target summed across participants. Error bars indicate standard errors.

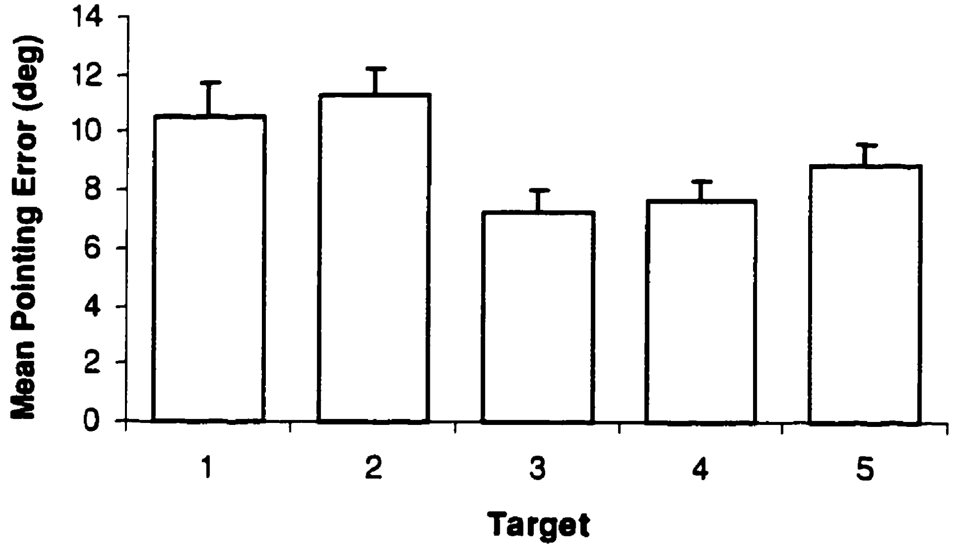
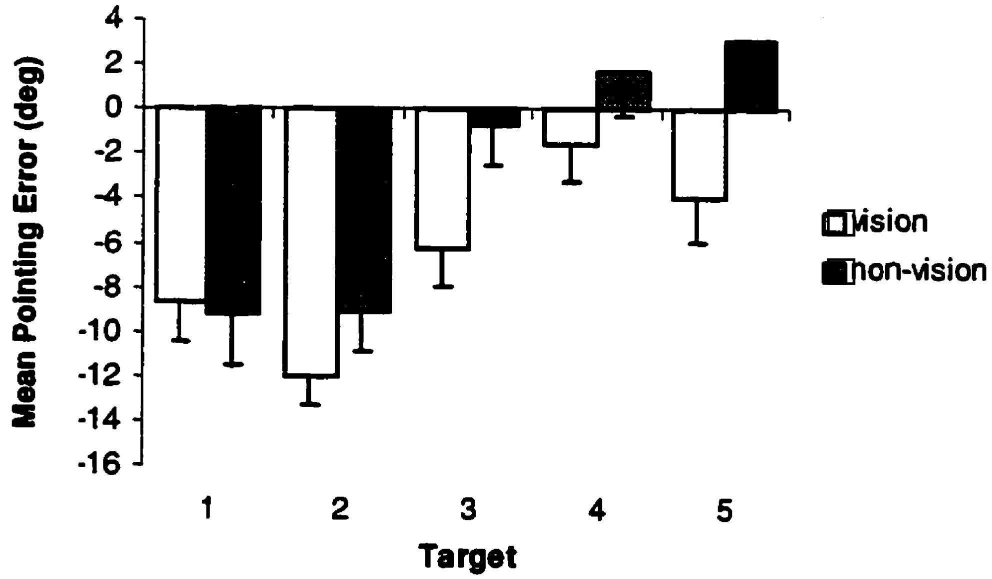


Figure 25. (Experiment 5). Mean signed pointing error at baseline for each group across each target. Negative pointing errors indicate that participants pointed to the *left* of the ideal target location. Error bars indicate standard errors.



Signed

Vision Pointing Group vs. Non-Vision Pointing Group

There was a main effect of the repeated factor, target, F (1, 28) = 9.87, p < .01. Inspection of the means indicated that participants had the most difficulty pointing accurately to target 1 after being led to the novel location without vision. This finding is in line with unsigned data. Figure 27 shows the mean signed pointing error for each target at test for experiments 4 and 5 and illustrates how target location affected pointing responses from the novel location.

WALKED HEADING ERRORS

Were participants' walked heading errors better than chance for target 4?

If participants did not know where target 4 was located after the non-visual walk to the novel location, their walked heading would not be different from chance. Twenty-four random numbers were generated to represent random or chance responses. Using a simple F-test (Howell, 1996) that examined the difference between two sample variances it was revealed that the variance generated by the random responses was more than 10 times larger than the variance generated by the responses of participants. If the ratio of the larger (random numbers) to the smaller (participants' responses) variance is greater than 4.0, heterogeneity of variance can be concluded. In this instance, such a result suggests that the responses of participants clustered around the ideal target location more than they were random and indicates that participants had some idea of the direction of target 4 from the novel location.

Figure 26. (Experiment 5). Mean unsigned pointing error at test for each target summed across participants from the vision and non-vision pointing groups. Error bars indicate standard errors.

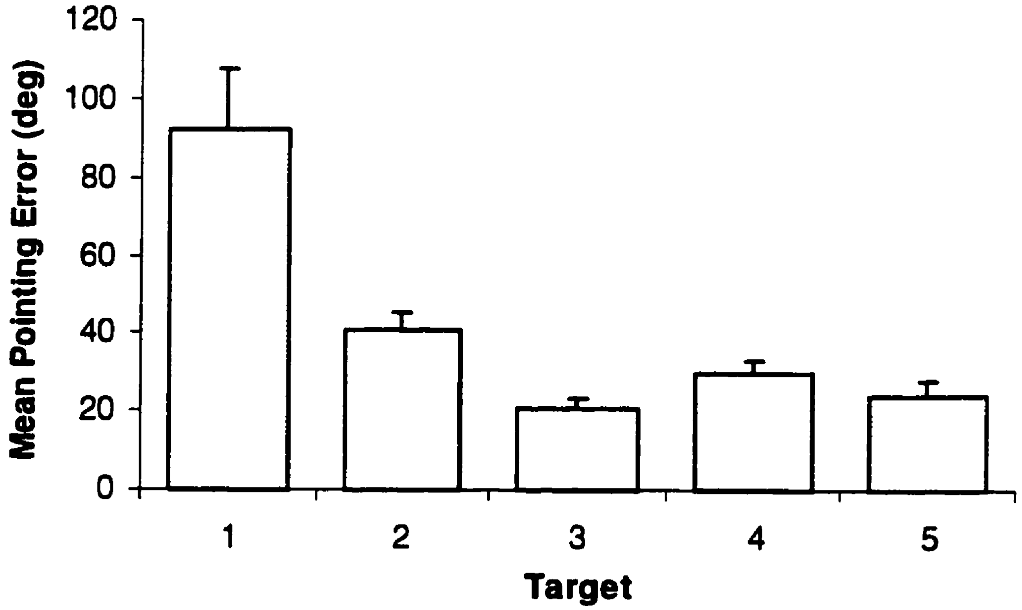
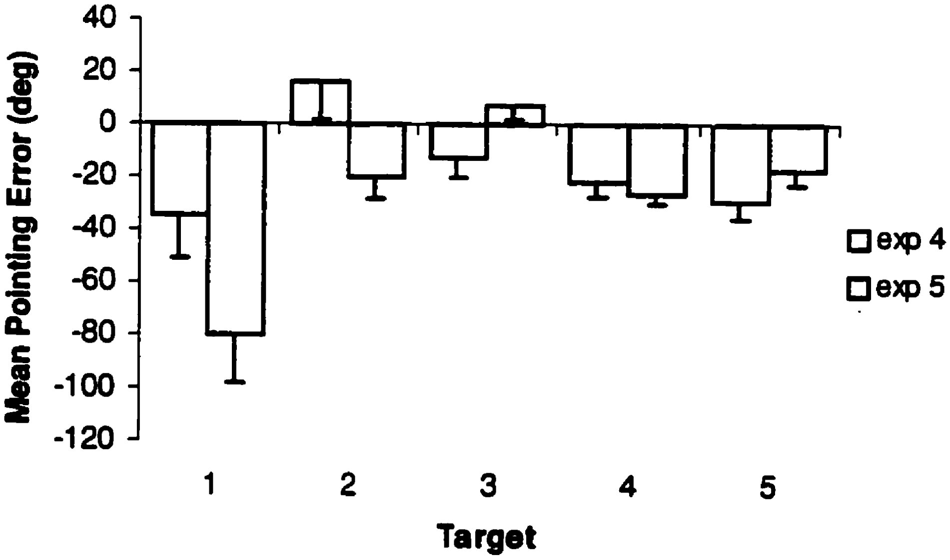


Figure 27. A comparison of the mean signed pointing error at test for each target for experiment 4 and 5. Negative pointing errors indicate a response to the *left* of the target and positive pointing errors indicate a response to the *right* of the target. Error bars indicate standard errors.



Unsigned

Vision Walking Group vs. Non-Vision Walking Group

There was no significant difference in walked heading error between the groups, F (1, 20) < 1.0, which suggests that, regardless of whether participants learned the object locations with vision or without vision, this did not affect the heading of their paths when attempting to walk towards target 4.

Signed

Vision Walking Group vs. Non-Vision Walking Group

A simple ANOVA that included the variables group and sex revealed a significant effect of group, F (1, 20) = 10.76, p < .005. This strong effect is due to the fact that the walked heading error of the vision group (M = 10.31 °, SE = 6.70 °) was biased to the right of the target while the heading error of the non-vision group (M = -18.49 °, SE = 5.69 °) was biased to the left of the target.

WALKED DISTANCE ERRORS

Were participants' walked distance responses better than chance for target 4?

If participants did not know where target 4 was located after the non-visual walk to the novel location, their walked distance responses would not be different from chance. One sample t-tests revealed that both the vision group (M = 4.1 m, SE = 0.105 m) and the non-vision group (M = 3.97 m, SE = 0.156 m) did not perform better than what would be expected by chance (2.44 m).

Unsigned

Vision Walking Group vs. Non-Vision Walking Group

No effects were found for walked distance error. Although this difference is not significant, it is interesting to note that the non-vision group (M = 0.625 m, SE = .16 m) produced less walked distance error than the vision group (M = 0.724 m, SE = .11). It seems that the forced fixation had a small effect on the performance of the vision group and less on the non-vision group.

Signed

Vision Walking Group vs. Non-Vision Walking Group

There were no signed differences between the walked distance of the vision and non-vision groups at test. Interestingly, 47 out of 48 participants overestimated the distance of the target. As a result, the mean signed walked distance error is the same as the unsigned for each group.

Pointing Angle vs. Walked Heading to Target 4: A Comparison of Response Outputs

As in the previous experiment, it was important to compare the differences in error produced when participants were asked to point in the direction of a target or walk to the same target to indicate its location.

Unsigned Errors

Recall that it was predicted that learning the locations of targets in space when central fixation was required would adversely affect the pointing heading accuracy but not walking heading accuracy. Again, the comparisons were made at target 4, as this was the only target to which participants in the walking groups responded. First, it was predicted that the mean unsigned pointing error of the vision group would increase to a value similar to the mean of the non-vision group. Second, for target 4 the heading error of the walking groups would not change significantly. If these effects were achieved, the experimental manipulation of central fixation would have been effective and would have eliminated the interaction between group and response output seen in the previous experiment.

An ANOVA conducted on group (vision/non-vision), condition (pointing/ walking) and gender revealed only a main effect of response output was significant, F (1, 40) = 4.36, $p < .05$. Examination of the means indicated that pointing and walking responses differed. Walking heading error (M = 20.27 °, SE = 3.22 °) was lower than pointing heading error (M = 29.82 °, SE = 3.18 °). To evaluate whether these differences in pointing and walking were found in the vision or non-vision group, more detailed post-hoc analyses were performed. No significant differences in mean unsigned heading error were found for the vision pointing (M = 23.05 °, SE = 2.79 °) or vision walking (M = 20.05 °, SE = 4.24 °) groups. However, when a post-hoc simple effects analysis was run on the heading errors for the non-vision pointing (M = 36.58 °, SE = 5.12 °) and non-vision walking (M = 20.5°, SE = 5.03 °) groups, it was found that these groups differed, F (1, 40) = 6.19, $p < .025$. It appears that the mean error of the non-vision pointing group was driving the overall effect of response output found above in the larger ANOVA.

Even though the interaction between response output and group was not significant, a post-hoc simple effects analysis was performed to statistically evaluate the first prediction mentioned above. The analysis showed that when targets were learned with vision, the mean pointing error was still significantly lower than the pointing error for the non-vision group, F (1, 40) = 4.37, p < .05. Thus although the mean error for the vision pointing group increased from the previous experiment, the central fixation manipulation did not significantly impact the ability to visually encode the spatial locations of the targets and to indicate their locations from the novel location.

Signed Errors

An analysis of the signed errors on the same variables revealed a main effect of group, F (1, 40) = 13.12, p < .005 where, overall, the vision group (M = - 3.89 °, SE = 5.1°) produced significantly less heading error than the non-vision group (M = - 26.3 °, SE = 4.53 °). The ANOVA also revealed a main effect of response output, F (1, 40) = 12.65, p < .005. In comparing the mean signed heading errors generated by the pointing and walking groups, participants asked to point (M = -26.1°, SE = 4.4 °) towards a randomly named target from the novel location produced significantly more error than participants who were asked to walk (M = -4.09 °, SE = 5.2 °) to the same target. Responses of both groups were biased to the left of the target.

Comparing Experiment 4 (no fixation) and Experiment 5 (central fixation)

The protocol of experiment 4 allowed participants in the vision condition to orient their eyes and their head in the direction of targets during the learning phase of the experiment. Experiment 5 did not permit this. Instead, participants in the vision group were asked to fixate on and read aloud numbers from a distant, centrally located board while they encoded the locations of the objects with their periphery. The following analyses compared the errors at baseline and at test for the groups in the no-fixation and fixation experiments.

Unsigned Baseline Findings

For performance at baseline, it was predicted that the mean unsigned pointing error of the vision and non-vision groups of the central fixation experiment would increase slightly from their baseline performance in experiment 4 when retinal and extra-retinal information about target location was available. The omnibus ANOVA on target, experiment number, group and gender, revealed a significant interaction between experiment number (4 vs. 5) and group (vision vs. non-vision), $\underline{F}$ (1, 88) = 4.95, $\underline{p} < .05$. Post-hoc simple effects indicated that the mean pointing errors of the vision and non-vision groups from experiment 4 did not differ from the mean pointing errors of the vision and non-vision groups of experiment 5. In addition, the mean pointing errors of the vision ($\underline{M}$ = 9.28 °, $\underline{SE}$ = .694 °) and non-vision ($\underline{M}$ = 8.67 °, $\underline{SE}$ = .84 °) groups from the central fixation experiment were not significantly different from each other $\underline{F} < 1.0$. In effect, these analyses show that the difference between the pointing error for the vision and non-vision groups at baseline disappeared in the present experiment. Figure 28 shows that the pointing error of the vision group in the present experiment increased but not significantly from the previous experiment. Surprisingly, the mean pointing error for the non-vision group actually decreased. It was suspected that the small amount of vision that participants in the non-vision group received for central fixation influenced their ability to perceive the direction they were being led during the learning phase.

The analysis also revealed an effect of target, F (2, 215) = 11.08, $p < .001$ and an uninterpretable 4-way interaction between target, experiment number, group and gender. To break down this interaction, separate ANOVAs analyzed target, experiment number and group at each gender. Results indicated that the 4-way interaction was driven by gender as the only effect was a highly significant effect of target for *females* F (2, 103) = 11.20, $p < .001$. Again, targets 1 and 2 generated the largest pointing error. No other effects or interactions were significant and there were no significant findings for the analysis with females and nothing was significant for males.

Signed Baseline Findings

Signed data were analyzed by a repeated measures ANOVA using experiment number, group and gender as variables. A main effect of target was found, F (2, 192) = 50.51, $p < .001$ as well as a target by group interaction, F (2, 192) = 4.08, $p < .025$. The non-vision group produced more error at all but one target location but the interaction is occurring as a result of the mixed rightward and leftward pointing responses. Both groups pointed to the left of targets 1, 2 and 3 but point to the right of target 4 and show a mixed pattern for target 5.

Test Findings

After participants were led to the novel location, half were asked to point towards the targets and the other half were asked to walk to target 4. An interaction between response output, pointing or walking, and group, vision or non-vision, was found for this target location in experiment 4 (refer to Figure 19). The purpose of experiment 5 was to examine whether this interaction was related to the preferential link between vision and pointing. It was hypothesized that locomotion was not as intimately linked to vision as pointing was and so locomotion performance should not be impaired if retinal and extra-retinal signals were uncoupled.

A simple ANOVA using experiment number, group, response output and gender revealed a main effect of group, F (1, 80) = 4.78, $p < .05$; the vision groups of both experiments combined produced less error than the non-vision groups combined. Because the important comparison was between the vision pointers of experiment 4 and the vision pointers of experiment 5, more detailed analyses were run on these groups. Results showed that, although the mean pointing error did increase in the predicted direction as a result of the manipulation, it was not a significant increase from the previous experiment F (1, 20) = 2.05, $p = .17$ (see Figure 29). This indicates that the forced central fixation did not have its desired effects. The non-vision pointing group of the present experiment did not differ significantly from the same group from experiment 4, $F < 1.0$ but they were not expected to differ. As predicted, forced central fixation during the learning phase did not affect walking performance; walked heading error for both the vision and non-vision walking groups of the present experiment did not change from the previous experiment.

There was also a main effect of response output, F (1, 80) = 6.35, $p < .025$; overall, pointing heading error was larger than walked heading error. However, these effects were qualified by a group by response output interaction, F (1, 80) = 6.53, p <

.025. It appears that combining data from both experiments strengthened the interaction between vision and non-vision and pointing and walking. This replication of experiment 4 supports the idea that non-visual walking might be a better index of an individual's knowledge of target location than non-visual pointing because the former was not affected by altering the congruence of retinal and extra-retinal input.

Figure 28. A comparison of the mean unsigned pointing errors at baseline between the vision and non-vision groups of experiments 4 and 5. Error bars indicate standard errors.

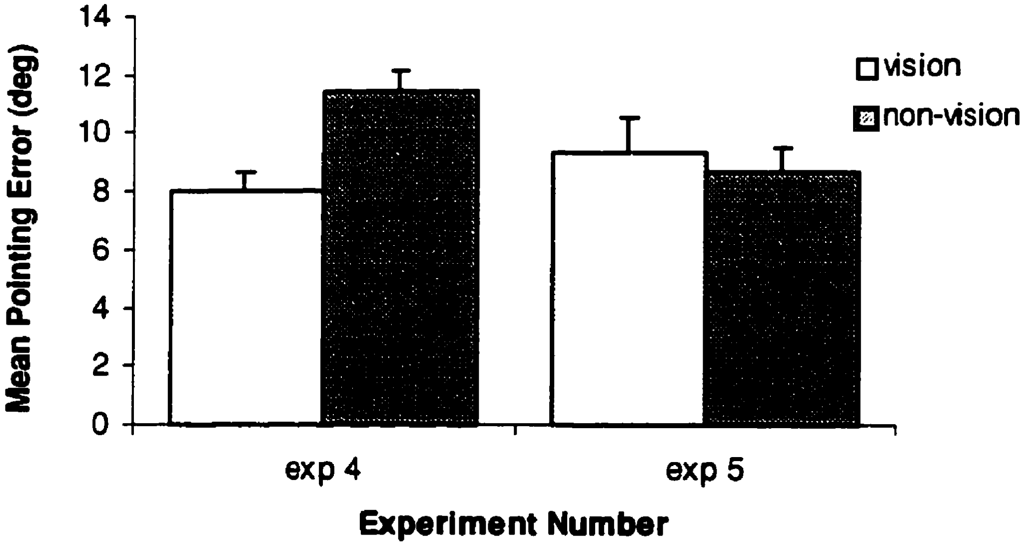
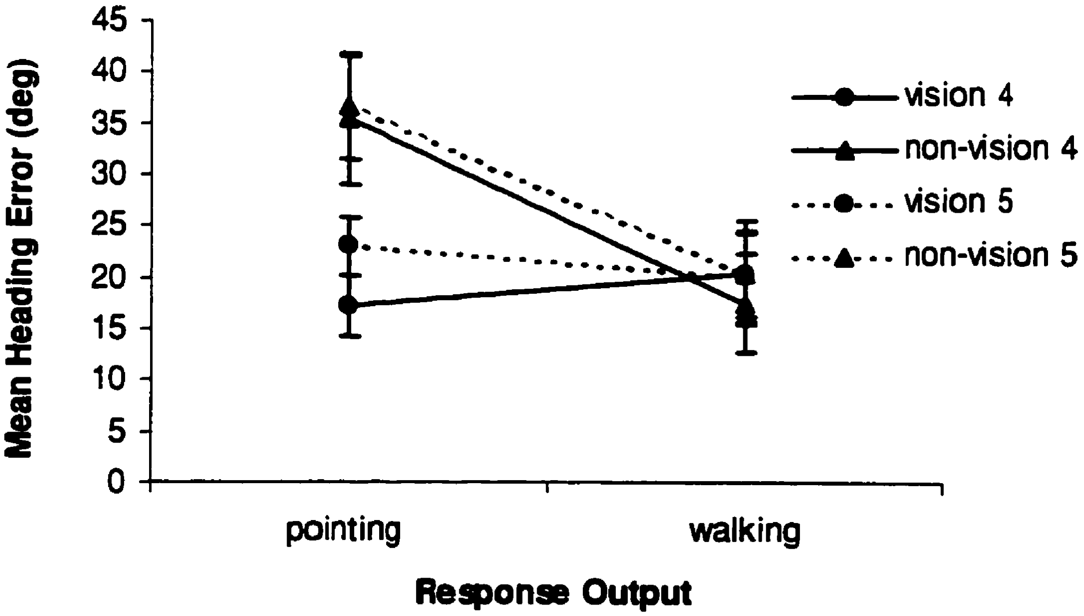


Figure 29. A comparison of the mean unsigned heading errors at test for the vision and non-vision groups at each response output for experiments 4 and 5. Error bars indicate standard errors.



DISCUSSION

Fixating on a centrally located target while encoding the spatial location of an arrangement of ground-level targets prevented concomitant retinal and extra-retinal information about location but appeared to have no significant effects on subsequent non-visual pointing when baseline performance was assessed. Comparing the vision group of the previous experiment where participants could actively fixate a target to encode its spatial location, with the vision group of the present experiment, forced central fixation did not appear to make a difference in pointing accuracy. This finding does not support the theory that both the eyes and the head must be oriented towards a target for accurate encoding of its' spatial location for subsequent non-visual pointing.

Fixating on a central target when one was learning target locations non-visually (baseline condition) decreased pointing error as compared to when absolutely no vision was available. There are two equally plausible explanations for this finding. The most obvious explanation is that this small amount of visual input was able to influence participants' sense of position, in effect supplementing the information about self-position provided by vestibular, somatosensory and efference copy signals. This suggests that vision was influential even though the visual information that was available was not particularly informative about target location, and at best, provided ambiguous distance cues. Another explanation, which does not necessarily preclude the former, is based on the idea the vestibular system contributes to our sense of head position, which subsequently provides perceptual feedback about orientation and, conceivably, direction. In order for participants in the non-vision group to maintain fixation throughout the walk to each target location, their head and eyes had to turn with respect to the orientation of their body. It is well known that the human vestibular system is very sensitive to small rotational accelerations of the head. Psychophysical experiments have established the average threshold of these accelerations to be on the order of 0.1 – 2.0 degrees/sec^2 (Geurdy, 1974) and normal, everyday movements of the head are much slower than this threshold (Geurdy, 1974). Therefore it is possible that, with each step towards the target location, participants' heads turned enough in the direction opposite to the direction of the walk to provide signals about head orientation in space. The vestibular signals, along with information about the initial walking heading and kinesthetic information from the neck muscles, were sufficient to render an estimate of perceived target direction. In essence, the vestibular system was able to account for the magnitude of the head's counter-rotation and its displacement from the body's orientation as participants turned their heads to keep the fixation point in sight while walking towards the target.

The effect of the central fixation was further diminished when participants were asked to indicate target location from a novel location in space. It was predicted that, at test, the errors produced by the vision-pointing group would be comparable to those produced by the non-vision-pointing group. Although the two groups did not differ at baseline, their errors diverged significantly when tested at target location 4 from the novel location. At this point our hypothesis appeared to be unsupported because the errors of the vision group were lower than those of the non-vision group and the interaction between group and response output was not significant. We considered that, even though the means of the four groups were very similar at test between the two experiments, perhaps the source of the interaction seen in experiment 4 was different than the source of the effects in experiment 5. However, after inspection of the signed pointing errors at test, it seems likely that the same processes were at work because the magnitude and direction of the errors were similar. We finally concluded that the hypothesis was not supported after comparing the errors produced by the vision and non-vision groups of the present experiment to the previous experiment. Even though the pointing error of the vision group in this experiment *increased* in the predicted direction, it was not a significant increase from the previous experiment. The data thus point to a number of possible conclusions. It is possible that what we found was evidence against the preferential link between the eye-pointing system in this context. But, based on previous research this conclusion seems unlikely as the effect of central fixation on non-visual pointing accuracy is robust and has been replicated by independent sources (Enright, 1995; Bock, 1986). Another possibility is that the interaction between the form of the response (pointing or walking) and the sensory input (vision or non-vision) is not related to the linkage between eye position and pointing. Although its likelihood seems remote, it is a logical possibility that two entirely different factors were responsible for the poor performance of the non-visual pointing group from these two experiments.

The second hypothesis predicted that non-visual walking performance accuracy would not be affected by manipulating the congruence of retinal and extra-retinal signals because locomotion is not as tightly linked to vision as is pointing. This hypothesis was supported by the results of the present experiment insofar as the effect found for the walking groups in the previous experiment was replicated. There was no change in the walked heading error for the vision and non-vision walking groups from experiment 4 to experiment 5, which suggests that walking was not affected by changes in the congruence of retinal and extra-retinal input (or head/body orientation incongruence in the case of the non-vision group). But, because the experimental manipulation did not significantly affect the performance of the vision pointing group, these conclusions about the link between locomotion and vision can only be tentative. Nevertheless, the successful replication of the walking accuracy across the two experiments suggests that there is something special about the locomotive response, even when target locations are originally learned without vision.

What was different about these two non-vision groups that one (pointing), but not the other (walking), should generate such a large heading error at test? Both groups received the same sensory input and training about target locations and both groups received the same non-visual walk to the novel location. The only thing that differed between the two groups was the type of response output that was required at test. It is believed that it was this change, from walking during training to pointing at test, that contributed to the poorer performance of the non-vision-pointing group. To appreciate this, consider that during non-visual locomotion, the internal representation of the environment is entirely dependent on the information acquired while learning that environment. Because the locations of targets were learned by walking blindfolded to and from their locations, space was mapped in such a way that the perceived spatial relationships (distances and directions) between the objects and the starting point were based on this non-visual locomotive input. In other words, the internal representation of that space was calibrated using the information acquired during the non-visual walks to each target location. A challenge arises when one is required to re-map or perceptually re-organize space for a response output that is much different from the way in which that space was originally calibrated or represented. The perceptual-motor transformations required to shift from a walking response to a pointing response would require more processing and would be subject to more spatial distortions than simply shifting from walking input to a walking output. Indeed, this sort of "calibration-dependent" learning can be seen by comparing the non-vision-walking group to the vision walking group; both performed with the same accuracy. Rieser, Pick, Ashmead and Garing (1995) examined whether individuals were able to adjust the calibrations of their motor outputs to compensate for changing environmental circumstances. For example, an individual first learned to walk without vision to a previously viewed target. They then experienced a new relation between their biomechanical activity (response output) and their surroundings by walking on a treadmill at one speed that was being towed at another speed (rearrangement phase). It was expected that when they were asked a second time to walk blindfolded to the previously viewed target that they would have recalibrated space based on the biomechanical output during the rearrangement phase and overestimate its distance. When they tested to see whether this calibration was generalizable over different motor outputs they found that throwing was the only motor output that could not be recalibrated by influencing walking but that other motor outputs that were related to walking could be recalibrated. Although this is not directly related to shifting from a walking to a pointing response output, it suggests that it is rather difficult to generalize an internal representation generated by one motor output, like walking, to a different motor output, like pointing. A counter argument to the perceptual-motor re-mapping explanation is that in the baseline condition, which also required pointing responses from the non-vision group, errors were relatively low. Although this is true, the merit of the explanation should not be affected because it was the performance at test that was most important as this was where the integrity of the spatial maps was being examined. Further, as mentioned previously, the spatial arrangements of the targets at baseline could have led to a restriction of range of possible responses which may have masked any differences in accuracy between the vision and non-vision groups. Perhaps because navigation generally requires walking, it has evolved as a response output for this spatial behaviour.

The influence of the walk to the novel location should also be re-evaluated. Recall that we were not able to completely rule out that the non-visual walk to the novel location influenced performance. In fact, it might be possible that it was the non-visual walk from the starting point to the novel position that was responsible for the increased response errors at test. Enright (1995) noted that, if an observer shifts their position after they visually encoded the location of a target, their non-visual pointing accuracy to this target from the new location would be affected. This error was further compounded by the fact that participants are generally poor at judging how far they have walked without vision (see experiment 2). Indeed, a number of researchers have commented on the fact that there are errors in the sensory processing of non-visual information and that these errors are cumulative (e.g. Barlow, 1964; Potegal, 1982; Etienne et al. 1988; Gallistel, 1990; Fujita et al. 1993). It appears that each of these explanations alone is not sufficient to account for the increase in errors at test and so it can only be concluded that it is a combination of both the non-visual walk and the change in response output that influenced performance. In these experiments, we were not able to tease apart the influences of these variables.

The Importance of Prior Visual Information Revisited

Perhaps it is not the congruence of the retinal and extra-retinal signals that are important for accurate pointing but that pointing responses in general are dependent on learning the spatial relations between objects with vision. This might explain why the vision pointing group performed with some accuracy in both experiments whereas the non-vision pointing groups did not. This also supports the idea that performance on certain types of non-visual navigation tasks (i.e. non-visual pointing) is accurate with prior vision but much less accurate when information for the task is acquired non-visually. Thus far we have no reasonable explanation for why the non-vision pointing group performed so poorly in comparison to the other groups but it is possible that there is some piece of information that participants in the vision group can use but that the non-vision group cannot. For instance, the vision group, although required to fixate a distant point, still received retinal information about the target's location. Because participants' eye movements were *not* controlled at any point after the learning phase it is possible that, at some point, they used the retinal coordinates of the target locations, thus obtaining some kind of efference copy information. Participants cold have then used this extra-retinal information about the target's location to help them solve the task. At no time during the experiment do participants in the non-vision group receive retinal information about target location.

GENERAL DISCUSSION

Taken together, the five studies presented in this thesis have attempted to contribute to our understanding of an individual's ability to utilize the non-visual sensory information available from non-visual locomotion to determine distance, direction and current position in space. Previous research that has examined the accuracy of non-visual locomotion and non-visual distance and direction estimation have studied how prior visual input impacts non-visual outputs like pointing or walking (e.g. Loomis et al. 1993; Rieser et al. 1986; Glausauer et al. 1994; Takei et al. 1997). In addition to replicating the findings of these studies, the experiments in this thesis have provided an explicit account of the relative contribution of non-visual sensory input to these behaviours. Non-visual locomotion was used not only as a measure of an individual's ability to estimate navigation vectors but was also used as the sole sensory input for spatial learning. By requiring participants to use non-visual sensory information to encode and store information about the locations of targets by estimating the distance and direction of travel, path integration ability and non-visual space representation was assessed.

The findings of these studies suggest that when non-visual information is the only source of information about the distance and direction of a target location from a point of origin, it is not quite sufficient for accurate place navigation. However, in no way does this mean that non-visual sensory information is unreliable or useless. On the contrary, these experiments showed that the combination of vestibular, kinesthetic and efference copy information influenced performance in subtle ways. Because individuals performed better than chance on many occasions it suggests that they were able to construct some kind of coherent representation of space without vision for subsequent action within that space and that they were able to path integrate with a modest degree of accuracy. However, there are a number of plausible reasons for why non-visual information alone is not sufficient for accurate navigation performance or at least why the performance of the non-visual group was not as good as individuals that received prior vision. First, non-visual information is derived from a group of senses with which sighted people have had little experience or practice; we are highly reliant on vision and become uncomfortable and cautious when asked to perform tasks without vision. It is possible that practice with non-visual information, such as walking a path without vision several times, would allow an individual to perform the tasks used in these experiments as well as one who had prior vision. Indeed, blind individuals have considerable practice navigating the world without vision and many studies have found no differences on many spatial performance tasks between congenitally blind, late-blind and blindfolded sighted individuals (see Thinus-Blanc and Gaunet, 1997). Next, the sensory systems involved in perceiving distance and direction of travel when vision is unavailable probably do not have the sharp spatial resolution that is afforded by vision. Although the vestibular apparatus is relatively sensitive to slight turns of the head as well as to linear acceleration, it is not really known whether the vestibular system is able to provide accurate estimations of such movements over longer distances or more complex actions like locomotion. Nevertheless, the general consensus is that, over short distances, like those used in the present experiments, the vestibular system allows for accurate reproduction of passively experienced distances and rotations (Israel et al. – 1997; Berthoz et al. 1995). Finally, one other explanation that has not been explored nor written about in the literature is that non-visual sensory information may simply have a short "sensory half-life" and, unlike visual information, decays quickly. The consequences of this are the increased errors seen in the non-vision groups as time passes and additional movements are experienced.

The data from these experiments also suggest that our estimations of distance and direction are different depending on the type of response output used to measure these estimations. We found that there was little cross talk between the data provided by each response output; map drawing did not explain pointing or walking errors. Based on this, we are led to believe that there is something unique about the spatial representations used to render a verbal response, a map drawing, a pointing and a walking response, and that perhaps there are different spatial representations for each response output. This argument suggests, then, that there is not one central representation of space that each response output uses to solve spatial problems. If a single representation of space could be used by each system interchangeably, we would have found that analyzing a drawing of space or requesting a verbal estimation of some spatial parameter would provide useful information about how that same individual walked in space. Instead, it is possible that what might be happening is that each response system (i.e. pointing, walking, drawing) draws spatial information from the same database and then appropriately shapes and organizes the information to form its unique representation of space in order to render the response. As such, the spatial representation that will be used by the locomotive system cannot be exchanged for one that would be used by the system that draws or points. In the end, no one response output is "better" than another as each is afforded its own advantages and the response type you use to examine navigation and related behaviours ultimately depends on what you are interested in studying.

This thesis also explicitly investigated whether there were any differences in performance accuracy between males and females. Past studies that have investigated gender differences in spatial ability commonly employ non-performance tasks such as map drawing or map remembering, verbal reports on navigation strategies or verbal estimations of distance and direction (e.g. Lawton, 1994; Lawton et al., 1996, Ward et al., 1986; Galea and Kimura, 1993). It is found that males typically employ different strategies to remember a map route than females (Galea and Kimura, 1993) and that males are better than females at recalling cardinal directions and Euclidean information from a map. Unfortunately, much of what we know about gender differences in spatial ability have come from these kinds of cognitive-perceptual and paper-pencil types of tasks and they suggest that males solve spatial tasks with more accuracy and with greater speed than females (see McGee, 1979). In our studies we compared the responses of males and females on both perceptual (non-locomotive) and performance types of tasks. We have found that gender differences are found in the tasks that required verbal responses but that the differences disappear when performance responses are examined. For example, when participants were asked to verbally estimate the distance of a visual target, males and females responded quite differently. However, when participants were asked to verbally estimate the distance they had walked without vision, there were no differences between the genders (experiment 2). Similarly, male and female participants did not differ in the accuracy of their reproductions of the distance to a target they had learned through non-visual locomotion but their verbal estimates of distances differed significantly (experiment 3). What is interesting about this difference between the genders is that it is closely related to the kind of response output used; a response output like locomotion, which is representative of a performance skill, appear to eliminate, or at least attenuate, the differences between the two genders.

Finally, a question may be raised about whether the performance of the vision group would have been more accurate had they been allowed to engage the neural systems that integrate visual motion and vestibular input. In other words, if the vision group were allowed to make some kind of movement during their encoding of the target locations, would they have performed better? Such a question is worthy of study in light of the fact that optic flow makes an important contribution to navigation by providing useful information about self- and object velocity when vision is available (personal communication, Frost, 1998).

The present studies have raised other issues and questions that could not be addressed in the scope of this thesis but which may be the basis of future research. First, for instance, recall from experiment 1 that the place navigation performance of participants who received a combination of visual and non-visual information about a target location was influenced in a manner much different from participants who received either visual or non-visual information alone. It was suspected that the information provided by vision led to one representation of the target's location while the non-visual information led to different representation of its location. It would be very interesting to study the effects of combined visual and non-visual sensory information on spatial representation. Second, more research should be conducted on the stability and clarity, over time, of the non-visual sensory trace. Is the non-visual sensory trace over-written in favor of new non-visual input or more reliable visual input? Does this information decay rapidly if it is not consolidated in some way? Understanding more about how long non-visual information can be retained and at what point it begins to decay would be helpful for future studies that make use of non-visual sensory input and would certainly provide further explanation for the findings stated here. Finally, this research has implications for more applied settings. The ability to accurately navigate is not only important for everyday life but it is essential to pilots and sailors who would have to rely on their internal navigational sense should their mechanical instruments malfunction. By studying how non-visual information contributes to navigation ability, we may also learn more about what navigational aids may be effective for blind people who do not feel confident traveling without a guide. This research also has implications for the future application, design and ultimately, the usefulness of virtual reality technology in the study of navigation. Virtual reality (VR) technology is fast becoming a very useful teaching tool in aviation, medicine and architecture. VR is also being used to explore, for example, the perceptual mechanisms involved in self-motion (Sun and Frost, 1997, 1998). Moreover, because there is flexibility in the way a given VR world can be constructed and in the way an individual may act or respond within that world, it becomes possible to study how space is represented and how spatial information is acquired and processed (e.g. Peruch, 1997; Marlin, Tong, David, and Frost, 1997). However, in order to use virtual reality for the study of navigation, the ways in which our senses and our brain integrate spatial information in real environments must be understood before attempting to study navigation in an environment where the contribution of non-visual information is virtually absent.

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Table 1. Unsigned and signed mean heading and distance errors, standard errors (in parentheses) for all groups in Experiment 1.

Group	Heading Error	Distance Error
Unsigned		
Vision	3.24° (0.4°)	0.525 m (0.06°)
Non-Vision	9.21° (1.1°)	0.846 m (0.10°)
Both	2.78° (0.3°)	0.500 m (0.06°)
Signed		
Vision	-0.28° (0.7°)*	-0.222 m (0.09)**
Non-Vision	-3.27° (1.9°)	-0.481 m (0.15)
Both	-0.94° (0.8°)	0.142 m (0.13)

Standard errors in parentheses
* a negative heading error indicates a response to the LEFT of the target
** a negative distance error indicates an undershoot of the target

Table 2. Mean unsigned distance errors (meters) for each target location

Target Location	1	2	3	4	5
Mean Unsigned Distance Errors (m)	0.61 (0.06)	0.46 (0.07)	0.71 (0.07) *	0.59 (0.07)	0.74 (0.08) *

Standard Error in parentheses (meters)
* $p < .01$ – paired t-test

Table 3. Eccentricity of target angles used in each experiment. Target angles are measured from 0 °. Angles less than 90 ° fall to the left of the individual and angles larger than 90 ° fall to the right of the individual.

	Target Number	Target Angle - Degrees from 0°
Experiment 1	1	81.9
	2	81.2
	3	104.6
	4	98.5
	5	92.8
Experiment 3	1	20.0
	2	45.0
	3	65.0
	4	90.0
	5	115.0
	6	135.0
	7	160.0
Experiment 4 & 5 (Baseline)	1	70.0
	2	35.4
	3	94.4
	4	103.9
	5	117.6
Experiment 4 & 5 (Test)	1	155.7
	2	49.6
	3	48.8
	4	90.0
	5	109.0

Table 4. Unsigned means and standard errors comparing pointing angle and walking heading for the vision and non-vision groups

	Pointing	Walking	*p*
Vision	17.2° (2.97°)	20.4° (4.26°)	NS
Non-Vision	35.3° (6.28°)	17.6° (4.88°)	< .05
p	< .02	NS	

Appendix 1. The schematic drawing of the court given to participants in Experiment 4 to draw the locations of the objects and the novel location that they learned during the experiment.