Chapter 5
The Effect of Translational and Rotational Body-Based Information on Navigation

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Abstract Physical locomotion provides internal (body-based) sensory information about the translational and rotational components of movement. This chapter starts by summarizing the characteristics of model-, small- and large-scale VE applications, and attributes of ecological validity that are important for the application of navigation research. The type of navigation participants performed, the scale and spatial extent of the environment, and the richness of the visual scene are used to provide a framework for a review of research into the effect of body-based information on navigation. The review resolves contradictions between previous studies' findings, identifies types of navigation interface that are suited to different applications, and highlights areas in which further research is needed. Applications that take place in small-scale environments, where maneuvering is the most demanding aspect of navigation, will benefit from full-walking interfaces. However, collision detection may not be needed because users avoid obstacles even when they are below eye-level. Applications that involve large-scale spaces (e.g., buildings or cities) just need to provide the translational component of body-based information, because it is only in unusual scenarios that the rotational component of body-based information produces any significant benefit. This opens up the opportunity of combining linear treadmill and walking-in-place interfaces with projection displays that provide a wide field of view.

5.1 Introduction

Navigation is central to many types of virtual environment (VE) applications. However, with only a few exceptions (mostly in military training), these applications use abstract navigation interfaces. That is, users press buttons and manipulate

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devices such as joysticks and mice to travel through a VE and look around, and are provided with minimal *body-based sensory information* about their movement. Given the difficulty that many users encounter when trying to learn spatial layouts in desktop VEs [1], which only provide visual information, it is likely that "walking" interfaces could have a widespread and beneficial impact on VE applications.

This chapter is divided into four main parts. The first summarizes the characteristics of VE applications from a navigational perspective, by mapping them onto different scales of environment (model vs. small vs. large). The second identifies attributes of ecological validity that should be considered when applying the results of navigation research to a given VE application. The third, and most substantive, part reviews experimental studies that have investigated the effect of body-based information on navigation, focusing on studies that investigated the rotational and/or translational *components* of body-based information, rather that different *cues* (proprioception, vestibular and efference copy) [2]. These studies are categorized according to type of navigation participants performed while acquiring knowledge of the environment (single-route vs. whole-environment), the scale of the environment (small vs. large), the environment's spatial extent, and the richness of the visual scene. The chapter concludes by using these research results to identify the types of navigation interface that are suited to different applications, and highlight areas in which further research is needed.

5.2 Applications of Virtual Environments

From a navigational perspective, VE applications [3–5] may be divided into three broad categories (see Table 5.1). The categories are defined by the scale of the environment in spatial cognition terms [6].

In the first category are *model-scale* applications, where users look around while remaining in one position (model-scale spaces, which in the real world would be placed on a table top, can be seen and reached from a single place). Examples include designing the layout of the cockpit of a car and training communication between the pilot and winch-man of search and rescue helicopters. Head-mounted displays (HMDs) are ideal for these applications, because they allow users to look around naturally by turning their head, with positional changes lying within the bounds of low-cost tracking devices (say, a 1 m^3). This means that effective navigation interfaces for these applications do not require a walking interface, so they are not considered further until the Conclusions section of this chapter.

The second category is *small-scale* applications, where users can resolve all of the detail necessary for navigation from a single place (e.g., any position in a room), but have to travel through the VE during usage. Examples range from analyzing the ease with which an engine may be assembled, or a control room layout for visibility, to being a witness in a virtual identity parade (a courtroom lineup, conducted using avatars in a VE). In these applications it is typically straightforward for users to

Table 5.1 Examples of VE applications that, in spatial cognition terms, are model-, small-, or large-scale

Application	Environment scale		
theme	Model	Small	Large
Design	Cockpit layout	Engine assembly Control room layout	Chemical plant Architecture Retail shop layout
Training	Close-range naval weaponry Helicopter crew collaboration	–	Search building Learn evacuation route
Health	–	Motor rehabilitation	Post-traumatic stress disorder
Science	Molecular docking	–	Data visualization
Other	–	Identity parade	Heritage and tourism Computer games

determine where they wish to move, but it is often non-trivial to make the maneuvers that are necessary for that movement.

The third category is *large-scale* applications where users travel through a large environment (e.g., a building, city, forest or dataset) over an extended period of time, integrating sensory information obtained during their movement to maintain knowledge of their location in the environment and avoid getting lost. Sometimes, and as with small-scale applications, maneuvering is non-trivial (e.g., when training to search a building for the enemy [7, 8]), but typically it is the acquisition of spatial knowledge that is the greatest navigational challenge.

5.3 Ecological Validity

Experimental (and especially laboratory) studies of navigation use stimuli and tasks that have been chosen to investigate specific hypotheses, and are sometimes simplified to an extreme. To assess the relevance of an experiment's findings, it is important to balance the generality of those findings with the ecological validity of the stimuli and tasks for a given type of VE application. In particular, attention should be paid to the VE's scale, extent and visual scene, the paths users follow during navigation and how frequently they follow them, and how users' knowledge is assessed.

A VE may be model-, small-, or large-scale in spatial cognition terms (see above). The cognitive processes involved for navigation in each of these differ substantially, as does the difficulty of and time required for users to acquire accurate spatial knowledge. For example, in a few minutes users can learn an environment's layout from a map (the map is effectively a model-scale representation of the environment), but such knowledge takes orders of magnitude more time to learn by direct navigation in the environment itself, which is large-scale [9], although knowledge gained in the latter will be ultimately more detailed. Thus, particular caution should be taken when applying the findings of research conducted in model- or small-scale environments [10–12] to applications that require users to navigate large-scale VEs.

To overcome the above issues with the scale of a VE, it is common for studies of full walking interfaces to condense an environment so that it fits within the physical space of a laboratory. This leads to a situation where the environment is large-scale, but its *spatial extent* (physical size) is small (say, less than 10 × 10 m) [13–15]. This is rather unrealistic (in both VE applications and the real world a large-scale environment is almost always also large in extent), but necessary for the purposes of the experiment. However, extent changes the time cost of traveling from one place to another and influences navigational behavior [16]. Few walking studies have actually investigated the effect of extent, but a notable exception is [17].

In early VE navigation studies it was rare for a visually rich environment to be used (a notable exception was [18]), but this richness is now more common, partly due to the ability of PC graphics cards to render complex scenes in real time. Real-world environments and modern VE applications typically contain a surfeit of visual cues, which compete to become landmarks and may be used in a different manner to landmarks in a visually impoverished setting [19]. Thus, apart from specialized applications such as training for evacuation during a fire, a rich visual scene is essential for ecological validity.

The paths people navigate in VEs and the real world often involve many navigational decisions. By contrast the paths used for some navigation research, particularly studies that investigate low-level mechanisms such as distance perception and path integration, are simplistic and so may engage different cognitive processes (e.g., working vs. long-term memory) and brain regions [20] than when users navigate in a real VE application. Most experimental studies only expose a participant once to an environment before testing, which has similarities with being a first-time visitor to a place, but is clearly different from settings that a user visits repeatedly and develops spatial knowledge of over an extended period of time. In those latter circumstances a user has more opportunity to learn the layout of the environment as a whole (survey knowledge).

Lastly, studies adopt a variety of measures, some of which are designed to assess specific aspects of users' route or survey knowledge, and others that are designed to assess to ephemeral concepts such as presence. These measures should be considered in the context of the tasks users perform in a given VE application before the relevance of research findings can be judged.

5.4 The Effect of Body-Based Information

This section reviews the findings of research into the effect of body-based information on navigation, and offers explanations for contradictions between some of the studies' findings. The review attempts to inform: (a) our basic understanding of how translational versus rotational body-based information affects human navigation, and (b) simplify the process of applying those findings to VE applications. In terms of scope, the review focuses on the effect of different components of body-based information (rotation vs. translation), rather than different cues, because during active walking users are provided with a full set of body-based cues. The criteria for inclusion in the review were that a study: (a) involved users changing both position and orientation as they navigated, and (b) investigated different components (rotational; translational) of body-based information, not just different cues (proprioception; vestibular; efference copy). Low-level studies that focused exclusively on rotational movement (e.g., [21]) or distance perception are omitted (e.g., [22]).

5.4.1 Review Framework

The studies that are reviewed are divided into four groups (see Table 5.2), which are dictated by the type of navigation participants performed while acquiring knowledge of the environment (single-route vs. whole-environment) and the scale of the environment (small vs. large). Single-route acquisition is where participants only navigated one specific route. Whole-environment acquisition is where participants either freely explored the environment or navigated to find target locations that were distributed around the environment, in specific but changing orders. The distinction between small- versus large-scale environments is explained above.

Spatial *extent* is classified as either small (room-sized; a maximum of approximately 10 × 10 m) or large (building-sized or greater). The richness of the *visual scene* is classified as low, medium or high. Low corresponds to environments where, apart from target landmarks, variations in the visual scene were just designed to provide optic flow. High corresponds to rich visual scenes that contained a surfeit of visual detail of deliberately added landmarks (e.g., at each junction in a building), and medium corresponds to scenes that did not belong clearly to either of the other categories.

The experimental results summarized in Table 5.2 are divided into *navigation* performance (time taken and distance traveled metrics that show how efficiently participants moved between places) and survey knowledge (*direction* estimates and straight line *distance* estimates). These survey metrics are the basic information people need if they are to know the location of places in relation to each other, or take shortcuts [30]. Absolute direction estimate errors were used, rather than signed errors that indicate response biases (e.g., see [31]) and, in all except the triangle completion studies (single-route acquisition/small-scale environments), the distance estimates were estimates of relative straight line distance, which are accurate if people have a well-developed cognitive map [9]. For a discussion of distance estimation methodologies, see [32].

Each type of results is subdivided into four columns: *Vis*, *Rot*, *Tran*, and *Full*. Vis is where participants were only provided with visual information (e.g., a desktop VE). Rot and Tran are where participants were provided with the rotational and translational component of body-based information, respectively, in addition to visual information. Full is where participants were physically walking through the

Table 5.2 Effect of body-based information on navigation performance and survey knowledge (direction and straight line distance estimates)

Study	Extent	Visual scene	Navigation				Direction estimates				Distance estimates			
			Vis	Rot	Tran	Full	Vis	Rot	Tran	Full	Vis	Rot	Tran	Full
Single-route acquisition and small-scale environments														
Klatzky et al. [23]	Small	Low					░	█						
Kearns et al. [24]	Small	Low					█			░	n.s.			n.s.
Peruch et al. [25]	Small	Low					░	░		█	░	▒		█
Single-route acquisition and large-scale environments														
Chance et al. [13]	Small	Low					░	▒		█				
Ruddle et al. (Expt. 2) [15]	Small	High		░		█								
Suma et al. (Exp. 1) [14]	Small	High		n.s.		n.s.								
Witmer et al. [18]	Large	High		░		█								
Grant et al. [26]	Large	High	░			█	n.s.			n.s.				
Waller et al. [2]	Large	High					░			█				
Waller et al. [27]	Large	High					n.s.			n.s.				
Whole-environment acquisition and small-scale environments														
Ruddle et al. (Expt. 2) [11]	Small	Low	░			█								
Riecke et al. [12]	Small	Low	░	█		█								
Ruddle et al. (Expt. 1) [11]	Small	Medium	░	░		█								
Whole-environment acquisition and large-scale environments														
Ruddle et al. (Expt. 1) [17]	Small	High	░	░		█	░	▒		█	▒	░		█
Ruddle et al. [28]	Large	Low	n.s.	n.s.			n.s.	n.s.			░	█		
Ruddle et al. [29]	Large	Medium	n.s.	n.s.			n.s.	n.s.			█	░		
Ruddle et al. (Expt. 2) [17]	Large	High	n.s.	n.s.	n.s.	n.s.	░	░	█	█	░	░	█	█

See *Review framework* for a detailed explanation

environment and, therefore, were provided with rotational and translational body-based information, as well as visual information. The terms Vis, Rot, Tran and Full are used as generic group names in the remainder of this article.

In Table 5.2, cells are blank if the relevant metric or category of body-based information was not investigated in a given study. For example, Chance et al. [13] only investigated direction estimates for Vis, Rot and Full conditions. If there was no significant difference for a given metric then all the categories of body-based information that were investigated in the study are marked as "n.s." (e.g., Vis and Full, for distance estimates in Kearns et al. [24]). Where a study reported statistically significant differences, shading shows the worst, inermediate and best performing conditions. The logic used to determine the shading is best explained using examples. Chance et al. [13] uses all three levels of shading because there was a main effect of direction estimate accuracy, pair-wise comparisons showed that the Full group performed significantly better than the Vis group, and performance of the Rot group was clearly intermediate. Ruddle et al. (Expt. 1) [17] uses the “worst” and “best” shading levels because there was a main effect of navigation performance, and pair-wise comparisons showed that the Full group performed significantly better than either of the other groups. The Riecke et al. [12] data refers to the number of revisits metric, which is more sensitive than the percentage of perfect trials. There was a main effect, and pair-wise comparisons indicated that the Full and Rot groups were equivalent, but there was a marginally significant difference between the Rot and Vis groups.

Caution should be taken when drawing conclusions from results that were statistically not significant. Sometimes this is due to there being no underlying difference. On other occasions it is due to a lack of statistical power, and this is particularly true in navigation studies, which often have large individual differences.

5.4.2 Studies Investigating the Effect of Body-Based Information

5.4.2.1 Single-Route Acquisition and Small-Scale Environments

All three of the studies included in this section [23–25] used a triangle completion paradigm (this involved being guided along two legs of a path and then being asked to point or return directly to the start point, which assesses a participant’s ability to take short cuts). Klatzky et al. reported a step change in performance between Vis and Rot groups of participants, with the latter performing accurately and the former not. By contrast, Kearns et al. (Experiments 1 and 3) reported a small but significant difference between Vis and Full groups, with the Vis group performing more accurately. The difference between the studies’ findings may be due to participants’ mode of response, because Klatzky’s pointed to where they would have to travel to return to a trial’s start point, and the errors were assumed to occur because the Vis group failed to update their cognitive heading. Kearns’ participants’ responded by traveling to where they thought the start point was located, and while doing so may have corrected their cognitive heading. Some support for this explanation is provided by subsequent research, which showed that the errors reported by Klatzy et al. did not occur if participants responded verbally [33].

Péruch et al. reported that participants who walked (a Full group) performed best and those who were in a Vis group performed worst, in direct contrast to the findings of Kearns et al. However, Péruch’s study combined responses from triangle completion trials with responses from trials in which participants had to reverse the two-leg path that had been traveled. In research by Ruddle et al. [15] substantially fewer errors were made by participants who physically walked and then reversed a path (a Full group) than participants who were in a Rot group. If a similar difference occurred in Péruch’s study then the Full group’s superior performance on path-reversal trials more than compensated for slightly inferior performance on the triangle completion trials, and that would explain the difference with Kearns et al’s findings.

Each of the above studies was designed to investigate specific low-level perceptual and cognitive processes that are involved in navigation. To do so, participants were either blindfolded or presented with optic flow visual information. Triangle completion is trivial to perform accurately in rich visual scenes [34] which, together with the simple (two leg) paths that participants followed, means that the above studies had little ecological validity with the environments and tasks used in VE applications.

5.4.2.2 Single-Route Acquisition and Large-Scale Environments

Compared with the above studies, investigations of the effect of body-based information that used single-route acquisition tasks and large-scale environments have produced more consistent findings. Whenever the results were statistically significant, the Full group performed best, and the worst performing group was either the Vis group (if such a group was part of the study) or the Rot group (if the study had no Vis group).

In identifying the above consistency in the findings, a number of caveats should be noted. First, Witmer et al. [18] asked participants to learn a route through either a real building (Full group) or a high visual fidelity VE model of the building (Rot group), and then tested training transfer to the real building. The Full group was superior in both training and testing, but the difference could have been caused by various factors that were associated with performing the task in the real world, not just the addition of translational body-based information. Second, Grant and Magee [26] also performed a training transfer study. The Full and Vis groups both trained in the VE, but there was not a significant difference between the groups' direction estimate accuracy when tested in that environment. A significant difference only occurred when navigational performance was tested in the equivalent real-world environment. Third, although Waller et al. [27] found no significant main effect for the accuracy of direction estimates, for the most complex routes (6–8 turns) the Full group's estimates were significantly more accurate than the other groups' estimates. Fourth, in both of Waller's studies [2, 27] the Full group moved actively, but the Vis group passively viewed movement that had been recorded by a camera worn by a person who walked. Fifth, Suma et al. [14] reported significant effects, but these were due to the poor performance of participants who used a move-where-pointing interface (a Vis group). There was not a significant difference for the time taken between a physical walking (Full) group and another Vis group, who used a move-where-looking interface, for the number of collisions with the environment's walls, or in recall and recognition tests about objects that had been in the environment. That contrasts with another study, where participants who physically walked (a Full group) were significantly better at both recognizing and correctly recalling the order of objects that had been in the environment than participants who were in a Rot group [15].

In summary, these large-scale environment studies indicate that navigating a route with full body-based information improves both the route and survey knowledge of participants. There is some evidence that rotational body-based information produces an intermediate accuracy of spatial knowledge, but only one study included factors of Vis versus Rot versus Full [13]. From an ecological validity perspective, these large-scale studies somewhat inevitably required participants to navigate routes that were more complex, and hence ecologically more valid, than the small-scale environment studies that were described in the previous section. It is also notable that all but one of the large-scale studies used a high-fidelity visual scene, unlike their small-scale counterparts. Finally, the pattern of results is independent of the spatial extent of the environment that was used.

5.4.2.3 Whole-Environment Acquisition and Small-Scale Environments

The experiments that used a whole-environment acquisition task in a small-scale environment have both consistencies and differences between their findings. A notable consistency is that participants tended to maneuver around objects in a VE when provided with a physical walking interface (a Full group), but collided with them when provided with interfaces that had less body-based information (Rot or Vis groups) [10, 11]. Participants' paths were also qualitatively different—curved with a walking interface but straight for participants in Rot and Vis groups.

Zanbaka et al. [10] gathered subjective responses from participants and measured their ability to maneuver. The other experiments quantified participants' ability to remember where they had traveled, and showed that participants in Full groups performed significantly better than those who were in Vis groups. However, there was an inconsistency in the findings for participants in Rot groups. When the environment was square those participants performed as poorly as participants who had no body-based information (a Vis group) [11], but when the environment was circular the Rot group's performance was comparable with that of a Full group [12]. Contrary to assertions made by the authors of the latter study, a likely explanation is that rotational body-based information is important when external (visual) orientation cues are absent (see also [35]).

5.4.2.4 Whole-Environment Acquisition and Large-Scale Environments

At first glance Table 5.2 appears to highlight several contradictions between the findings of this fourth category of experiment, but the following explanations make the underlying pattern of results more consistent. First, consider differences between Rot and Vis groups. In none of the studies did a statistical test show a significant difference between these groups for navigational performance. For survey knowledge, the differences between these groups appears to be metric-dependent in Experiment 1 of [17] (Table 5.2 indicates that direction estimates were worst for the Rot group, but distance estimates were worst for the Vis group), but this is due to post-hoc tests showing that the Full group differed significantly from the Vis group (direction estimates) and Rot group (distance estimates). There are indications that, with greater statistical power, other posthoc comparisons may also have been significant, which would have led to the same pattern of results as for navigational performance in that experiment, and all metrics for Experiment 2 of that study. However, the contradiction between the findings for distance estimates [28, 29] remains unexplained (if the findings had been the opposite way around then they could have been explained by environment layout, which was orthogonal [28] versus oblique [29]; see previous section).

Both Full and Trans groups have the benefit of translational body-based information, which accounts for the significantly more accurate direction and distance estimates made by those groups than Vis and Rot groups in both experiments of Ruddle et al. [17], and the significantly better navigational performance of the Full group in Experiment 1 of that study. The lack of an effect of translational body-based information in Experiment 2 may be because the increased (and ecologically more valid) spatial extent meant that participants had considerably more time to process visual information as they navigated, so body-based information made less contribution to their development of spatial knowledge. Alternatively, it is possible that the environment was not complex enough for a statistically significant effect of translational body-based information to occur (a ceiling effect).

Lastly, Suma et al's Experiment 2 also used whole-environment acquisition and a large-scale environment [14]. The Full group collided with the VE's walls less often than the Vis group, but the difference in the distance the groups traveled (greater for the Full group) in the time that each participant was given may have been due to either an inbuilt speed restriction or insufficient practice with the virtual travel interfaces that were provided for the Vis and Rot groups. Metrics involving a cognition questionnaire and a map placement test produced non-significant results between the groups, which is common for these tests' lack of sensitivity.

5.5 Summary and Conclusions for VE Applications

So how can the findings of experimental studies of body-based information inform the design of navigation interfaces for VE applications? Table 5.3 summarizes the answer to this question from a navigation perspective, taking into account the need for users to maneuver and develop of spatial knowledge, but does not attempt to consider other factors such as cost.

5.5.1 Model-Scale Environments

In applications that use environments which in spatial cognition terms are model-scale then users need to be able to look around, but make only localized adjust-

Table 5.3 Navigation interfaces that would benefit different types of VE applications

Navigation interface	Environment scale		
	Model	Small	Large
Abstract (Vis group)	–	–	Data visualization
Orientation-tracked (Rot group)	Cockpit layout Close-range naval weaponry Helicopter crew collaboration Molecular docking	–	–
Linear treadmill (Trans group)	–	Motor rehabilitation	Chemical plant Architecture Retail shop layout Learn evacuation route Heritage and tourism Computer games
Walking (Full group)	–	Engine assembly Control room layout Identity parade	Search building Post-traumatic stress disorder

ments to their position. Therefore, orientation-tracking (the type of interface used by Rot groups in the studies described above) is sufficient and there is no need for a full walking interface, as evidenced by a number of successful, military training applications [3].

5.5.2 *Small-Scale Environments*

In VE applications that utilize a small-scale environment, users generally know where they wish to travel, so the primary navigational challenge is maneuvering. The studies show a qualitative difference in people's maneuverability with Full (walking) interfaces, compared with Rot and Vis (abstract) interfaces, coupled with objective data that show that users collide with objects within the environment significantly less often when a walking interface is used [10, 11, 14]. This reduction takes place without the need to implement collision detection/feedback in the VE software, because users have a natural tendency to avoid objects so long as the interface provides sufficient maneuverability. Therefore, there is a clear indication that a walking interface is beneficial for applications such as engine assembly design, control room layout design and virtual identity parades, though cheaper, carefully designed desktop alternatives should also be considered (e.g., see [8]).

Control room layout combines the same requirement for maneuverability with the need for users to be spatially aware of the environment they are designing, which also benefits significantly from the provision of a walking interface [11, 12]. As with other small-scale applications, the spatial extent of the environments means that it is technically feasible to implement walking by tracking users in an empty room that contains the environment on a 1:1 scale, but a hybrid real/virtual walking interface may prove more practical [10].

Motor rehabilitation applications are concerned with a patient's gait, and so only require translational body-based information. This may be provided via a linear treadmill or a specialist exoskeleton-based device, but questions remain about the medical benefits of integrating such devices within a VE [36].

5.5.3 Large-Scale Environments

For applications that use large-scale VEs the consensus result is that a full walking interface is required [13, 15, 26], and probably necessary in applications that also require maneuverability (e.g., military training for searching a building; but see also [7, 8]). However, in a study that was unique in including a Trans condition, that condition was as effective as a Full condition in allowing participants to acquire spatial knowledge [17]. This highlights an opportunity for preserving the benefit to users while simplifying the technology used for walking interfaces. For example, although omnidirectional treadmills can be constructed [37], linear treadmills are simpler to design and so are smaller, cheaper and more reliable.

An exception is likely to be data visualization applications, because the scale involved (e.g., in genomics) is several orders of magnitude greater than other large-scale applications. Given that "magic" interfaces (interfaces that allow users to make movements that would be impossible in the real world, e.g., jump between widely separated places) [4] will always be needed if users are to move rapidly and precisely between levels of detail such as chromosome → base pair, such applications are likely to remain based on abstract navigation interfaces.

5.5.4 Further Research

The main area that requires further research into navigation interfaces is applications that use large-scale environments. One priority is to thoroughly evaluate techniques that allow the navigation of large spatial extents via walking movements made within a much smaller locality (treadmill, walking-in-place [38], and redirected walking [39]). Such interfaces are currently unproven, and we need to understand their effect on participants' navigational performance and the rate at which they develop route- and survey-type spatial knowledge. A second priority is to evaluate these interfaces with projection displays, because they hold advantages over HMDs in terms of image resolution and field of view.

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