Trails, Rails, and Over-Reliance: How Navigation Assistance Affects Route-Finding and Spatial Learning in Virtual Environments

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Abstract

Many novices struggle with navigation in 3D virtual environments — they frequently get lost and are unable to find objects and locations. In some virtual environments, novices are provided with *navigation assistance* (e.g., mini-maps, directional markers, or glowing trails) that help them move around in the world. However, it is possible that providing navigation assistance could lead to over-reliance, where the novice's dependence on the assist means that they never develop a mental model of the environment that would allow them to navigate on their own. To investigate both the benefits and potential risks of navigation assistance in virtual environments, we carried out two online studies in which participants carried out route-finding tasks with different types of navigation assistance. Participants completed training trials, in which they practiced a set of routes with the assist, and transfer trials, in which they had to navigate without the assist. The studies focus on two questions: whether assistance improves performance and user experience when it is present, and whether assistance leads to over-reliance and a drop in performance when the assist is removed. For the first question, both studies found that navigation assistance substantially improved performance and subjective experience while it was present — clearly showing that assistance can improve virtual environments for novices. For the second question, we found mixed evidence regarding the problem of over-reliance: the first study showed no performance differences between the highest and lowest levels of navigation assistance when the assist was turned off; the second study showed that there was a performance reduction when the assist was removed, but that the size of the reduction was much smaller than the improvement provided during training. We found that even when the navigation assist was extreme (e.g., pressing a button to be automatically taken in the correct direction), participants were still able to navigate the trained routes, suggesting that incidental learning does successfully occur in virtual environments. Our studies suggest that designers of virtual environments should strongly consider providing navigation assistance: assists can improve a novice user's performance and experience by reducing navigation problems, and the risks of over-reliance appear to be small in comparison to the benefits for inexperienced users.

Keywords: Virtual Environments, Navigation, Skill Development

1. Introduction

Three-dimensional virtual environments (VEs) are now an extremely common platform for digital interaction: VEs are regularly used for game worlds (e.g., *World of Warcraft*, *Team Fortress 2*, or *Skyrim*), for training environments (e.g., aircraft or driving simulators, emergency procedures training), for exploratory educational activities (e.g., virtual museums and art galleries), for architectural previews (e.g., walkthroughs of planned buildings), and for social interaction (e.g., *Second Life*, *There*, *Metaverse*). There are many types of 3D virtual environments, but all VEs are spatial environments in which users must *navigate* from place to place. Navigation is "coordinated and goal-directed movement through the environment" (Montello, 2005, p. 257) and includes two main components: route finding (selecting a goal location and planning a path to that goal — using strategy, memory, and decision making) and locomotion (actually moving through the space to reach the destination) (Montello, 2005).

Previous studies have shown that navigation and spatial learning in 3D virtual environments are difficult for many users (e.g., Darken and Sibert, 1996b; Jul and Furnas, 1997; Dubois et al., 2021) — more so than in the physical world. There are several possible reasons for this difficulty, such as the reduced kinaesthetic feedback of virtual locomotion, the reduced field of view, the relative lack of visual details and distinctiveness that can be used as landmarks, and the lack of non-visual sensory information (Waller et al., 1998). In addition, the size of the virtual environment, the density of objects within it, and the amount of movement required can also affect navigation (Darken and Sibert, 1993).

These difficulties have led designers of several VEs to provide navigation assists to users. Many different types of assist have been considered, such as verbal directions, superimposed arrows, compasses, maps showing the user's location, audio cues, landmarks, or even glowing trails that the user can follow to reach a destination (Moura and El-Nasr, 2014; Marples, 2017). Some of these assists are directly inspired by those available in the physical world while others are only possible within virtual environments.

Studies have shown that navigation assists can be effective in improving navigation performance (e.g., Münzer et al., 2012; Dijk et al., 2003). However, there is little understanding of the longer-term effects of navigation assists on spatial learning of the environment — in particular, whether assists can lead to users becoming overly reliant on the assist, leading to reduced spatial learning of locations, routes, and the overall layout of the environment (Thorndyke and Goldin, 1983; Thorndyke and Hayes-Roth, 1982; Thorndyke and Stasz, 1980). That is, navigation assists may help novices in the short term, but if users come to depend on the assist, they may be unable to navigate effectively when the assist is not available.

The unavailability of navigation assists could be a frequent occurrence in many virtual environments. For example, if the system does not know the user's destination (e.g., in an open-world game), it cannot provide an assist; or, if the user decides to take a shortcut or change their destination in the middle of a route, any provided assist will be incorrect and the user will need to navigate using only their spatial memory.

The risk of over-reliance on a navigation assist is an example of the *guidance hypothesis* (Schmidt et al., 2018). A common finding in previous studies of skill development and learning is that guidance improves performance for novices when it is present, but at the cost of reduced learning that causes a performance drop when the guidance is removed (Schmidt et al., 2018; Armstrong, 1970; Prather, 1971; Singer and Pease, 1976; Waters, 1930; Holding and Macrae, 1964; Macrae and Holding, 1966; Winstein et al., 1994). The reduction in learning can arise because guidance allows users to pay less attention to feedback and to expend less effort overall — previous studies have shown that intentionality and effort strongly affect learning (Schmidt et al., 2018; Ehret, 2002).

Navigation, however, is different from many of the skills tested in past work on the guidance hypothesis, because spatial learning has also been shown to occur *incidentally* and without intentional effort from the learner (Andrade and Meudell, 1993; van Asselen et al., 2005; Hasher and Zacks, 1979). For example, a learner can acquire landmark and route knowledge simply by following a guide through an environment (van Asselen et al., 2005). This natural ability to learn about a 3D space may arise because an understanding of our surroundings was critical for the survival of early humans. There is some debate, however, around how much spatial learning occurs incidentally, and there are studies that point to real-world navigation assists such as global positioning systems (GPS) contributing to problems in spatial learning (e.g., Burnett and Lee, 2005; Ishikawa et al., 2008; Leshed et al., 2008).

These contrasting theories mean that it is difficult to predict the effect that navigation assistance will have on spatial learning of a virtual environment. To provide new empirical knowledge about this issue, we carried out two studies[1] that provided different levels of navigation assistance for novices in virtual environments, and measured both the effect on performance (when the assist was present) and the effect on learning (when the assist was taken away). We tested several conditions that provided different levels of assistance and required different levels of effort from the user: no assistance at all, a map of the environment (either with or without the user's location shown), a glowing trail that the user could follow, and an "on rails" condition where users only had to press a key to continue moving in the correct direction.

For both studies, we had two research questions: (RQ1) Will navigation assistance improve performance and user experience when it is present? and (RQ2), will navigation assistance hinder spatial learning and cause over-reliance on the assist?

The first study tested three types of assistance that provided increasing levels of guidance (a static map, a map showing the user's location, and a glowing trail to the destination). Our results showed that the two higher levels of navigational assistance substantially improved both performance and subjective experience (RQ1), and that the higher assistance levels did **not** reduce participants' spatial knowledge of the environment — in all assistance conditions, participants could navigate the environment at a similar performance level after the assistance was removed (RQ2).

In the second study, we chose assistance conditions that explored an even wider range of user effort — a baseline condition with no map (which required more effort than any of the conditions in the first study), a glowing trail, and an "on rails" condition where participants only had to press a key to keep moving in the correct direction (thus requiring very little navigational effort). Results from the second study showed that the higher levels of assistance again substantially improved performance and user experience (RQ1); but unlike the first study, both of the higher assistance levels led to reduced performance compared to the no-assistance condition, once the assists were removed (RQ2). However, in a retention test one week after the main study (also with assists removed), all of the conditions performed similarly.

Together, these two studies provide several contributions that can change the way designers of virtual environments think about and apply navigation assistance.

- We show that navigation assistance substantially improves novices' navigation performance in virtual environments, and also substantially improves subjective experience.
- We show that the amount of user effort required for navigation does not accurately predict spatial learning of the environment: Study 1 found no difference in performance once assists were removed, comparing between the most-effortful and least-effortful forms of training; Study 2 only found an advantage for the highest-effort condition, and this difference largely disappeared after a week.
- We show that although more extreme forms of navigation assistance may slightly hinder the development of spatial memory compared to a no-assist condition, the effects are not disastrous: participants who trained with higher levels of assistance in Study 2 were still able to successfully navigate without the assists, and the benefit of having the assist outweighed any detriment.

Our studies suggest that navigation assistance provides substantial benefits and relatively small drawbacks for novices in virtual environments. Our results add to our understanding of how assistance affects spatial learning, and provide useful information for designers who want to make their systems more accessible to novices.

[1]The first study was initially published in the Proceedings of the Annual Symposium on Computer-Human Interaction in Play (Johanson et al., 2017); here we present a revised and re-analyzed version. The second study has not been published elsewhere.

2. Related Work

2.1. Learning with Guidance

Before discussing the skill of navigation and how guidance affects navigation, we present related work on different types of guidance as well as the general effects of guidance on skill learning.

Skill learning can generally occur without any explicit support or guidance, through a trial-and-error approach where a learner makes errors and observes the results until the correct response is acquired (Holding and Macrae, 1964; Singer, 1980; Maxwell et al., 2001; Prather, 1971). The role of guidance is to aid a learner so that they can execute skills with reduced errors (Singer, 1980; Schmidt et al., 2018). Learning in this way has been described as "guided" learning (Singer and Pease, 1976, 1978), "errorless" learning (Prather, 1971; Singer and Gaines, 1975; Maxwell et al., 2001; Howard, 2003), or "error-free" learning (Singer and Gaines, 1975; Singer, 1980; Maxwell et al., 2001; Johnson, 2004). However, there is debate as to whether or not making mistakes is essential to learning psychomotor skills (Holding and Macrae, 1964; Singer and Pease, 1976; Singer, 1980; Schmidt et al., 1989; Maxwell et al., 2001; Johnson, 2004; Schmidt et al., 2018), as identifying and correcting mistakes is often a key component of many theories of learning (such as operant conditioning (Wingfield, 1979) and experiential learning (Kolb, 1984)).

2.1.1. Types of Guidance

Guidance refers to instructions or assistance given to the learner by some external source before performing an action or while an action is ongoing. The goal of guidance systems is to assist learners in forming mental representations of the task they are trying to complete (Honeybourne et al., 2000). Guidance can also assist learners less directly, as it is known to have motivating effects for novices (Tomporowski, 2003). Guidance can either *precede* the execution of a task or occur *concurrently*, and can be presented mechanically, visually, or verbally (though we do not look at verbal guidance in this work).

Visual guidance is guidance that is presented to the learner with the intent of helping the learner develop a mental image of the task as well as how to complete it (Honeybourne et al., 2000). Visual guidance that precedes task execution takes the form of videos, charts, visual assists, or demonstrations (Honeybourne et al., 2000; Newell, 1981). Visual guidance that is presented concurrently takes the form of visual assists that the learner can leverage while carrying out the task, provided by an instructor (e.g., following a demonstration (Honeybourne et al., 2000)) or a software system (e.g., participants drawing a pattern could be shown the desired pattern by a computer monitor if they veer off-target (Howard, 2003)).

Mechanical guidance is any type of guidance that introduces a mechanical restriction on the learner to minimize errors or force a particular response (Newell, 1981; Honeybourne et al., 2000). Mechanical guidance is primarily provided during an action (Newell, 1981) and often guarantees that performance will be high (Winstein et al., 1994).

2.1.2. Efficacy of Guidance

The guidance used in our work — navigation assistance — is concurrent guidance that is either visual or mechanical, presented concurrently with the task of navigation. This type of guidance, for the most part, significantly improves *performance* while it is present, but potentially at the cost of reduced *learning* when evaluated by testing the participants again without the guidance (Schmidt et al., 2018; Armstrong, 1970; Prather, 1971; Singer and Pease, 1976; Waters, 1930; Holding and Macrae, 1964; Macrae and Holding, 1966; Winstein et al., 1994).

However, it must be noted that although several different experiments have shown a similar reduction in learning, the tasks used in those experiments were relatively simple (e.g., reproducing specific patterns (Armstrong, 1970), or manipulating specific inputs with one's hands and feet (Singer and Pease, 1976)). Such tasks are not difficult to learn using inherent response-produced feedback and therefore the findings may not apply to more complex tasks (Wulf and Shea, 2002). For example, findings for a study involving a ski simulator found that providing mechanical guidance benefited performance and learning (Wulf et al., 1998), and similar findings exist in the context of musical training (Grindlay, 2008) and gymnastics (Heinen et al., 2009). One example of mechanical guidance found in games is aim assistance. Vicencio-Moreira and colleagues found that aim assistance was an effective way to improve short-term performance (Vicencio-Moreira et al., 2014, 2015), and Gutwin and colleagues found that long-term use of aim assistance had no detrimental effect on learning (Gutwin et al., 2016).

It is also worth considering the efficacy of visual guidance given before the task — in particular, demonstrations. The mechanical ("on rails") guidance utilized in this work would allow participants to simply observe the environment around them as they have the correct path demonstrated for them. Studies have found that allowing participants to observe a demonstration of a task improves performance when compared to no demonstration (Pollock and Lee, 1992; McCullagh and Meyer, 1997; Rohbanfard and Proteau, 2011). These demonstrations are effective when they are able to reduce uncertainty on the part of the learner (Newell, 1981). In one example, Pollock and Lee tested the effect of watching another person play a game (Microsoft's *Olympic Decathlon* (Smith, 1982)) on performance and found that participants' performance was improved by watching another player play before playing themselves, regardless of whether the other player was an expert or a novice at the game (Pollock and Lee, 1992).

2.2. Navigation

A wide variety of research has been carried out to investigate the ways that humans learn and perform navigation in real-world environments — for example, researchers have looked at the development of spatial knowledge in children (e.g., Hardwick et al., 1976), sex differences in navigation (e.g., Chen et al., 2009; Lawton and Kallai, 2002), and theoretical models for navigation (e.g., Chen and Stanney, 1999). One major focus in navigation research is on wayfinding, the process by which people orient themselves to an environment and move from place to place. Early work identified three kinds of knowledge that are important for wayfinding, and that are associated with increasing spatial understanding (Thorndyke and Goldin, 1983; Thorndyke and Hayes-Roth, 1982; Thorndyke and Stasz, 1980):

- *Landmark knowledge* involves remembering specific objects or settings in an environment — such as a statue or a building in a city centre.
- *Route knowledge* involves understanding how to navigate between specific locations, and the actions required to reproduce a specific path between them. Route knowledge often builds on landmark knowledge (e.g., by linking different landmarks together).
- *Survey knowledge* is a map-like mental representation of an environment and is the highest form of spatial understanding. Survey knowledge allows people to navigate skillfully, estimate relative distances, and choose alternate routes to objectives.

There are two ways in which people can gain this spatial understanding of an environment (Darken and Sibert, 1996b). First, people learn through direct exposure to their surroundings — that is, simply being in an environment and moving through it. Second, external information sources such as maps provide other forms of spatial learning. When used in an actual navigation task, maps require that users identify their own location on the map, and then translate orientations, directions, and distances from the map representation to the actual environment.

2.2.1. Navigating Virtual Environments

Navigation in virtual environments has also been extensively studied. One main interest is in whether virtual environments can be used as training simulations for real-world navigation (Waller et al., 1998), and whether spatial knowledge and wayfinding ability transfer to real environments.

Researchers have also identified that navigational difficulties are common in virtual environments (e.g., Darken and Sibert, 1996b; Jul and Furnas, 1997; Dubois et al., 2021): "Virtual world navigators may wander aimlessly when attempting to find a place for the first time. They may then have difficulty relocating places recently visited. They are often unable to grasp the overall topological structure of the space" (Darken and Sibert, 1996b, p. 166).

To combat these difficulties, previous work has also looked at a variety of navigational aids to improve navigation efficiency. The value of landmarks has led researchers to consider the idea of allowing users to place visual markers, having the system create a visual trail showing where users have been, or having a fixed marker to provide a consistent indication of north (Darken and Sibert, 1996b,a). Results with these forms of assistance are mixed, however: adding a simple compass did not substantially improve navigation performance (Darken and Peterson, 2014), and trails can quickly clutter an environment. Designers of other virtual environments, such as digital games, have created a variety of navigation aids for users. These are discussed in Section 2.2.4 and the effects of such assists on spatial learning is discussed in Section 2.2.5.

2.2.2. Incidental versus Intentional Spatial Learning

A continuing debate concerns the relationship between spatial knowledge acquisition and intentionality. Studies indicate that at least some aspects of location learning occur automatically (Andrade and Meudell, 1993; Hasher and Zacks, 1979). For example, one study showed that recall of word locations was unaffected by the difficulty of a concurrent task (Andrade and Meudell, 1993). Other work, however, shows the importance of intention; studies have shown that when people focused their attention on a route through a building, they were better able to draw a map of that path (van Asselen et al., 2005), and that even a long experience with an environment may still result in poor survey knowledge (Chase, 1983). In particular, passive observation of the environment can allow one to acquire route knowledge, though survey knowledge seems to require more intentional effort (van Asselen et al., 2005; Chrastil and Warren, 2011).

2.2.3. How the Design of Virtual Environments Affects Navigation Difficulty

Virtual environments are generally considered to be more difficult to navigate than physical-world environments (Ruddle, 2001; Darken and Sibert, 1996b; Jul and Furnas, 1997; Waller et al., 1998). This is due to the reduced interface fidelity (lack of kinesthetic feedback, and a reduced field of view) and environment fidelity of virtual environments (lack of visual detail that can be used as landmarks along with a lack of non-visual sensory information) (Waller et al., 1998). Designers can therefore make virtual environments easier to navigate by increasing the visual fidelity of the environment.

Three additional factors affect navigation difficulty. First, the most significant is the *size* of the environment: environments that are small with minimal opportunity for exploration will be easier to navigate than environments that are large and complex (Moura and El-Nasr, 2014; Darken and Sibert, 1993). A second factor is *density*: a sparsely populated world has fewer objects of interest to leverage in navigation (Darken and Sibert, 1993). Third, *activity* is also an important factor: an environment where the position of objects changes over time is more difficult to navigate than if all objects remain stationary (Darken and Sibert, 1993).

2.2.4. Navigation Assists in Virtual Environments

Guidance within virtual environments is provided in a variety of ways. Researchers have identified a variety of navigation assists that can be found within virtual environments (in digital games in particular) (Marples, 2017; Moura and El-Nasr, 2014). Moura and El-Nasr categorize navigation assists as being either directional signs, identification signs, or orientation signs, with some assists fitting into multiple categories (Moura and El-Nasr, 2014). First, directional signs inform players where to go and what to do — for example, compasses, maps, GPS (maps which show one's location), arrows, or markers (see Figure 1 for examples from games). Second, identification signs indicate to

Figure 1: A variety of different types of navigation assistance found in virtual environments and games. This includes arrows, compasses, mini-maps, indicators, quest markers, and visual highlighting. From left to right, screenshots are from *Skyrim*, *Midtown Madness*, *Metal Slug*, *World of Warcraft*, and *Wolfenstein: Enemy Territory*.

players when they have reached their destinations — for example, markers, signs, or GPS (see the quest markers from *Skyrim* (Bethesda Game Studios, 2011) in Figure 1 and *Diablo 2 Resurrected* (Blizzard Entertainment, 2021) in Figure 3). Third, orientation signs inform users of their relative position within the environment — for example, maps that show the user's location.

Navigation assists can also be categorized as being presented separately from the environment or being situated within the environment. For those that are presented separately from the environment, some of the most common are maps, compasses, GPS, and arrows. Maps can be brought up via a menu or hotkey and can be shown full-screen or can be continually visible in the form of mini-maps (Marples, 2017). Maps are 2D representations of the 3D environment and are often augmented with other useful information, such as the user's current location (i.e., a GPS), as well as the locations of objectives, items, or other users. In some games, the map is revealed as a player explores the environment; players then know which areas of the environment they have or have not explored (Marples, 2017). Compasses are sometimes shown separately (as in *Skyrim* (Bethesda Game Studios, 2011), Figure 1) from the map or alongside the map (as in *World of Warcraft* (Blizzard Entertainment, 2004) or *Wolfenstein: Enemy Territory* (Splash Damage, 2003), Figure 1). These compasses show the user their current direction of travel and can also be augmented with additional information such as the direction of objectives. Arrows are also commonly placed within the environment to indicate the required direction of travel. For example, as part of the game's heads-up-display, *Midtown Madness 2* (Angel Studies, 2000) provides players with a yellow arrow that indicates the direction the player needs to travel to reach the objective (see Figure 1). As a simpler example, *Metal Slug* (Nazca Corporation, 1996) prompts the player to move to the right at certain times to make progress within the game (see Figure 1).

Navigation assists that exist within the environment itself are commonly found as indicators, arrows, trails, and highlights. For example, the same indicators that appear on many maps or compasses also appear within the environment itself: e.g., the quest markers in *Skyrim* and *Diablo 2 Resurrected* (see Figures 1 and 3). Arrows and signs are often placed into the environment itself as they would appear in the physical world (see Figure 2). Many games also make use of visual highlighting to direct a player's attention to important navigational information. For example, *Mirror's Edge* (DICE, 2008) uses the colour red to indicate to the player which objects they need to climb or interact with next (Figure 3). Finally, some games show players a visible trail within the environment to follow to reach their destination. For example, *Fable II* (Lionhead Studios, 2008) and *Neverwinter* (Cryptic Studios, 2013) have particle trails which can be turned on or off through the user interface (Figure 4). Sometimes this is part of a gameplay mechanic and provided only temporarily; in *Skyrim*, magic users have access to a "clairvoyance" spell that temporarily reveals

Figure 2: Ways that navigation assistance can be included directly within a virtual environment itself. From left to right, screenshots are from *Half-Life*, *Counter-Strike: Global Offensive*, and *Morrowind*.

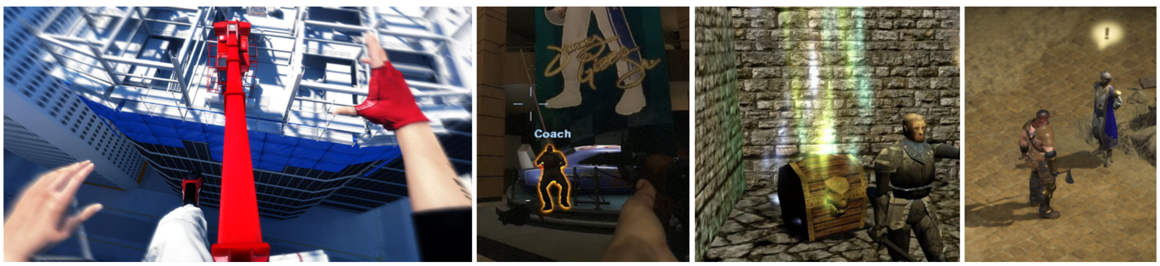


Figure 3: Examples of how the objects within the environment can be highlighted to indicate the direction of travel or important objects within the environment. From left to right, screenshots are from *Mirror's Edge*, *Left 4 Dead 2*, *Neverwinter Nights*, and *Diablo 2 Resurrected*.

the exact route to a quest marker with a smoke trail (Figure 4).

One final type of navigation assistance, commonly used in 3D games, is the guided tour (Moura and El-Nasr, 2014; Marples, 2017). Guided tours are often presented as scenes that walk a user through the environment or direct a user's attention to a specific object, providing a demonstration of how to navigate through the environment.

2.2.5. Effects of Navigation Assists on Spatial Learning

Navigation assists can affect spatial learning in different ways. (Khan and Rahman, 2017) suggest that assistance that reduces the user's mental effort interferes with spatial learning (Khan and Rahman, 2017; Craik and Lockhart, 1972). Therefore, reducing decisions during navigation can negatively affect spatial learning (Khan and Rahman, 2017; Bakdash et al., 2008). Other work has found that learners were less able to remember landmarks if navigation aid was provided (Gardony et al., 2013), although the authors attribute this effect to the navigation aid dividing the learner's attention. Similarly, (van Asselen et al., 2005) found that having a learner follow another person impaired their survey knowledge formation, although learners still acquired route knowledge. Khan and colleagues claim that maps in particular interfere with spatial learning because they place a cognitive load on the learner (Khan and Rahman, 2017), who must perform mental rotations to make use of the map (as described by (Darken and Peterson, 2014)). However, other researchers have pointed out that the map is a source of information that can provide a learner with survey knowledge (Darken and Sibert, 1996a). Recent research has also looked at the effects of guidance systems such as GPS and has found that people can become overly focused on the directions provided by external guidance, hindering the development of their spatial knowledge (e.g., Burnett and Lee, 2005; Ishikawa et al., 2008; Leshed et al., 2008).

Figure 4: Two examples of trail guidance, from *Fable 2* (left) and *Skyrim* (right).

3. Materials and Methods for Both Studies

We conducted two online studies[2] to answer our research questions relating to the efficacy of navigation guidance for navigation performance and user experience (when assistance is present) and the potential for reduced spatial learning due to over-reliance on the assist (when the assistance is removed). We designed and implemented a system that allowed online participants to navigate virtual environments between specific start and end points (i.e., routes). The system could vary the amount of navigation assistance provided to the participant, as described below.

Both studies involved a set of phases: a tutorial, in which participants were introduced to the environment and the route-finding tasks; a training phase, in which participants carried out tasks with navigation assistance; a transfer test, in which participants navigated routes with the assist removed; and (in Study 2 only) a retention test, in which participants navigated routes without assistance, but one week after their final training.

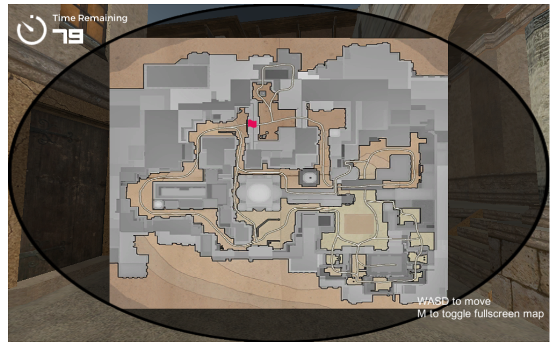
3.1. Virtual Environment

We used a virtual environment that was extracted from the commercial game *Wolfenstein: Enemy Territory*. The game's source code and tools are freely available, so we downloaded the game level and edited it using the GtkRadiant application (id Software, 2018) to remove all unneeded objects relating to game logic, leaving only the level's geometry and textures. The compiled level was then converted into a standard 3D model that was imported into the Unity game engine (Unity Technologies, 2018). Other 3D assets from the game were placed by hand within the environment (such as a tank and a truck) to be used as landmarks. We implemented first-person movement and view controls in Unity to match what is seen in typical games (WASD movement and mouse-based view control); we also created custom implementations of the different types of navigation assistance and added experiment infrastructure to present a set of routes and navigation tasks to the user.

We used the "Gold Rush" level (Figures 6 and 7) which presents a fictional town in northern Africa, with most of its routes located outside. The town has a variety of streets, walls, buildings, passages, plazas, and staircases. There are several naturalistic landmarks such as palm trees in

[2]Portions of Study 1 were reported in a CHI Play 2017 paper (Johanson et al., 2017). The version here presents an expanded and revised analysis of the data from the virtual environment that matches the one used in Study 2, to better allow comparison across the two studies.

(a) The interface with map assistance. No mini-map is provided.



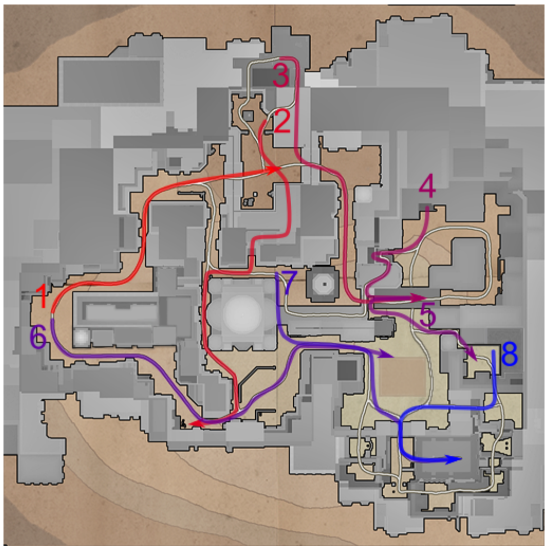
(b) The full-screen map with the map assistance version of the interface. No mini-map is provided, and the map does not show the user's current location.

(c) The interface with position assistance. At top right is the minimap that shows where the user is located (as a yellow circle) within the environment in relation to the flag. Users could also open the full-screen map, which also showed their position.

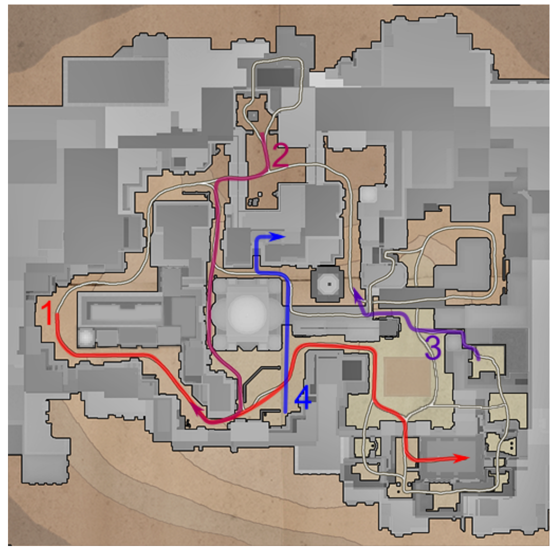
(d) The interface with trail assistance, showing the white trail that users could follow to be taken to the destination. This also the interface from the position assistance version.

Figure 5: Interfaces used for the three conditions of Study 1's training tasks.

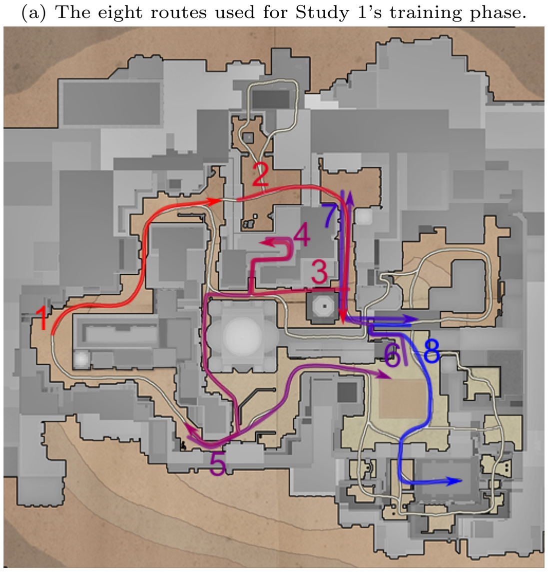
Figure 6: The first-person view of the "Gold Rush" environment from *Wolfenstein: Enemy Territory.*



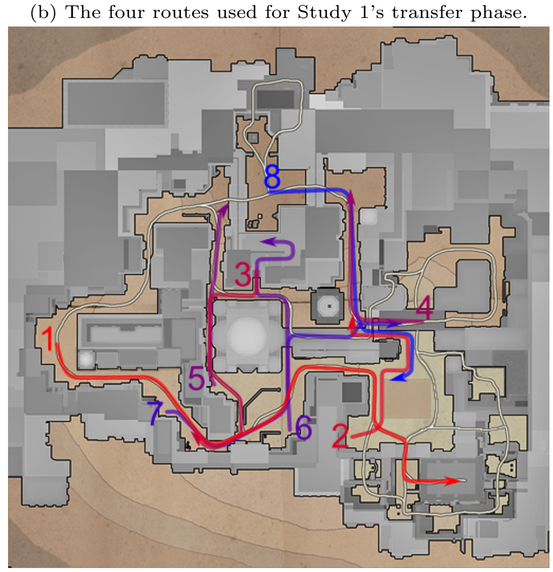
(a) The eight routes used for Study 1's training phase.



(b) The four routes used for Study 1's transfer phase.



(c) The eight routes used for Study 2's training and retention phases.



(d) The eight routes used for Study 2's transfer phase.

Figure 7: Overhead views of the "Gold Rush" environment, showing the routes used in Study 1 and 2.

a town square, vehicles including carts and tanks, and multi-story towers. This level was chosen because it had an adequate level of complexity with multiple possible routes to each destination.

A few details of the level were changed between Study 1 and Study 2. Because Study 2 did not provide a map, it was possible for participants in the no-assist condition to become lost — therefore, we slightly modified the environment for Study 2 to make two areas without landmarks inaccessible, reducing the overall chance of participants being unable to find the target destination.

3.2. Types of Navigation Assistance

Both studies introduced three levels of navigation assistance that were provided to participants during the training phase of the experiment.

3.2.1. Study 1

We designed three types of navigation assistance that varied in the amount of required navigation effort (see Figure 5).

Map Assistance. With map assistance, the participant had access to a full-screen pop-up map (invoked with the M key) that showed the target destination (see Figures 5a and 5b). In this condition, participants had to identify their own position on the map, plan a route to the destination, and translate directions and distances from the map view to the first-person environment.

Position Assistance. With position assistance, the same map as described above was also available, but with the participant's current position on the map now marked (see Figure 5c). Additionally, the interface included a mini-map in the top right corner of the screen. Similar to mini-maps found in other games (Zagata and Medyńska-Gulij, 2023), the mini-map was circular, player-centred, and used a north-up orthographic projection of the environment. Both maps included an icon indicating the participant's current location and direction (similar to the user icon used in Google Maps). In this condition, participants could see their dynamic progress on the map views — and if they navigated solely by focusing on the map, there was less of a requirement to translate information to the first-person view.

Trail Assistance. With trail assistance, the interface additionally showed the path to the destination as a solid white line drawn in the 3D environment (see Figure 5d). The two maps described above were also available: these showed the participant's location (but did not show the trail). The trail line was a guide only, and participants could take any route they wanted to the destination. The trail visual effect is similar to the navigational assists used in several commercial games, as discussed above. In this condition, participants had to expend far less effort than with the other interfaces — they did not have to identify their location or plan a route, and could simply follow the trail to the destination.

3.2.2. Study 2

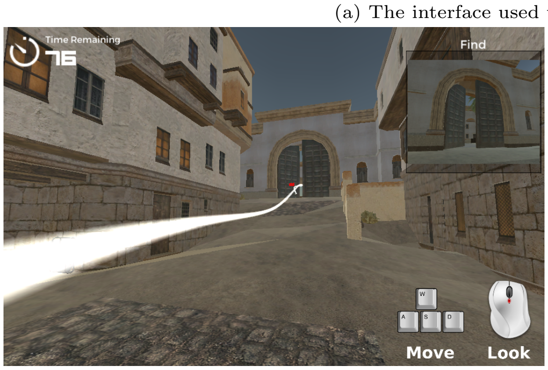
For Study 2, we developed three different types of navigation assistance to explore a greater range of required navigational effort (see Figure 8).

No Assistance. In this condition, participants navigated using only the first-person view: no maps or visual guides were provided (see Figure 8a). Participants were given a screenshot indicating the landmark to navigate to and had to find it on their own — this condition represents the maximum navigational effort in the study, as participants had to develop a spatial understanding of the environment using only the first-person view.

Trail Assistance. With trail assistance, the route that the participant was intended to take was indicated using a glowing white within the first-person environment (see Figure 8b). This condition was similar to the one used in Study 1 (except that no maps were available in Study 2).

Rail Assistance. With rail assistance, when the participant held down a key, they would move forward towards the destination (i.e., the participant was "on rails"), using the same route as would be indicated with trail assistance (see Figure 8c). Participants could look around in any direction while moving and still move in the correct direction. No trail was shown, and no maps were available.

(a) The interface used when there was no assistance.



(b) The interface showing the trail assistance. The white trail indicates the route to the destination.

(c) The interface showing the rail assistance. Nothing additional is shown in the game, but the shown controls are different (participants could only press the W key).

Figure 8: Interfaces for the three conditions in Study 2's training tasks.

(a) The interface used for Study 1's transfer phase. No assistance was provided to the user, not even the map.

(b) The interface used for Study 2's transfer and retention phases. No assistance was provided to the user (equivalent to the no-assist condition).

Figure 9: Interfaces used for transfer tasks (Study 1 and Study 2) and retention tasks (Study 2). In these tasks, users were asked to navigate to a landmark shown in the top-right corner of the screen.

3.3. Navigation Tasks

Both studies had participants complete a series of navigation tasks. In each task, the participant was placed at a starting location in the environment and had to navigate to a target destination (either a red flag on a pole or an obvious landmark such as a tank or a truck). The target destination was communicated to the participant either using the overview map (in Study 1 training tasks) or by showing the user a picture of the target landmark. Participants moved through the environment using the WASD keys to move forward, left, backward, or right (except for the rails assistance condition in Study 2, in which participants could only press the W key to move along the rail). Participants could look around the environment by moving the mouse.

3.3.1. Study 1

Study 1 had three different versions of the navigation task: a tutorial version, a training version, and a transfer version. In the *tutorial* version, participants had no navigation assistance and the route used a linear path — there were no decisions to be made regarding the direction of travel. The tutorial introduced participants to the controls and allowed them to ensure that their computer system would perform well enough to handle the rest of the study.

Tasks in the *training* phase (shown in Figure 5) took place over three days, with participants attempting a fixed set of eight routes each day, and with assistance depending on the condition that participants were assigned to (one of map, position, or trail assistance). All participants had access to the full-screen map (accessed by pressing the M key); the map showed the current target destination as a red flag icon. For each route, participants travelled between predefined start and destination locations. A 90-second time limit was given for each route to ensure that the participant could make progress in the study (although typical times to traverse a single route ranged from 5-25 seconds). The eight routes were the same on each day and were presented in the same order.

Tasks in the *transfer* phase (shown in Figure 9a) took place after the final training phase; participants were asked to complete an additional four routes without any assistance, not even a map. The four routes were different than those used in training, and instead of displaying the target destination on the map, an image of a target landmark (e.g., a truck) was displayed and participants were instructed to travel directly to that landmark. The landmarks were objects that participants had seen during training (e.g., they were beside the flags used in training, or they were on a required route); however, the routes differed because they started at different locations. There was no prior indication during the study that participants would be tested on their ability to navigate to these landmarks; we hypothesized that participants could acquire spatial information incidentally as they were navigating the training routes.

3.3.2. Study 2

Study 2 had four different versions of the navigation task: a tutorial version, a training version, a transfer version, and a retention version. The first three were similar to the equivalent versions in Study 1, so only the differences will be described here.

The *tutorial* was similar to Study 1, except that the navigation assistance for the assigned condition was also present in the tutorial because the controls for the rail assistance condition were slightly different (only the W key was used for movement instead of the WASD keys).

The *training* phase took place over four days instead of three. Three different types of assistance were used (no assist, trail assist, or rail assist) and participants were instructed to navigate to a landmark (permanently shown in the corner of their screen) rather than a point on a map.

The *transfer* phase (Figure 9b) took place one day after the last day of training instead of on the last training day; participants completed eight new routes instead of the four used in Study 1. The routes for the transfer phase had new starting locations, but the landmarks used as destinations were all objects that participants had encountered during training. As in Study 1, participants completed these routes with no assistance.

The *retention* phase took place one week after the transfer phase and asked participants to complete the same routes as they had trained on but without assistance. Retention tasks were only used in Study 2.

3.4. Procedure

Both studies were deployed on a custom website built using an existing web framework designed to aid the creation of online studies (Johanson, 2020). This website presented the questionnaires as HTML forms and embedded the game directly into the web browser using WebGL. Upon opening the website, participants would be asked to read a consent form and provide informed consent before being directed to the questionnaires and navigation tasks. Because both studies took place over several days, participants were invited back via an email (sent anonymously via Amazon's Mechanical Turk API) at the start of each day.

3.4.1. Study 1

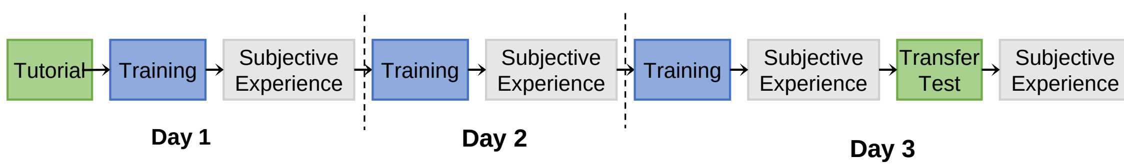


Figure 10: Procedure for Study 1. Green and blue boxes indicate navigation tasks (blue: assist present; green: no assist). Grey boxes indicate questionnaires.

The overall procedure for Study 1 is diagrammed in Figure 10. Participants first completed the tutorial version of the navigation task and then completed a questionnaire related to their gaming experience. This was presented as a separate qualification task that participants needed to complete to be eligible for participation in the study. Participants who had an adequate framerate (over 45 frames per second) and stated that they were "not at all" or only "slightly" experienced with the Gold Rush environment were invited to complete the rest of the study.

Participants who accepted this invitation were assigned to one of the types of assistance and then completed demographics and individual-differences questionnaires. They then began the training phase where they navigated eight training routes. After the eight routes, they answered questions relating to subjective experience. On the next day, participants completed the training again and responded to the same questions about subjective experience. This was repeated a third time on the final day, followed by the transfer version of the navigation task and a final round of the same subjective experience questions.

3.4.2. Study 2

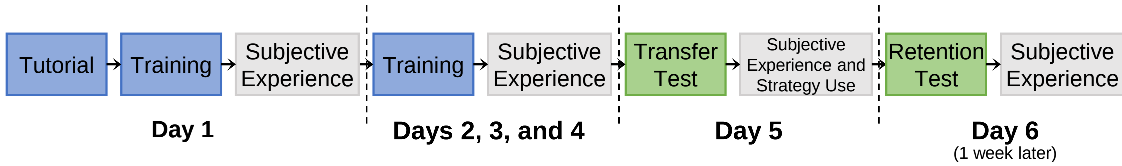


Figure 11: Procedure for Study 2. Green and blue boxes indicate navigation tasks (blue: assist present; green: no assist). Grey boxes indicate questionnaires.

The overall procedure for Study 2 is diagrammed in Figure 11. Participants completed questionnaires relating to demographics and individual differences before carrying out the tutorial task. Participants then began the training tasks; after the routes were completed, they responded to questions relating to subjective experience. The training procedure was the same on days two, three, and four. As in Study 1, participants were invited back each day using email reminders.

On the fifth day, participants completed the transfer version of the navigation task, answered the same questions relating to subjective experience, and also answered two additional questions relating to navigation strategy. One week later, participants completed the retention version of the navigation task and the same questions about subjective experience.

3.5. Measures

Both studies measured aspects of individual differences that might affect one's ability to navigate an environment, navigation performance outcomes, and subjective experience outcomes.

3.5.1. Study 1

The following measures of individual differences were collected at the start of the study:

- **Gaming Expertise.** We asked participants questions to establish their gaming expertise: how much they self-identified as a gamer, their experience with video games, their experience with keyboard-and-mouse input in games, their FPS (first-person shooter) experience, and their experience with 3D games. These questions were included because prior experience navigating virtual environments in games could affect how (and how well) participants navigated during the study (Burigat and Chittaro, 2007).

- **Immersive Tendencies.** We used the Immersive Tendencies Questionnaire (ITQ) (Witmer and Singer, 1998) to measure participants' tendency to experience presence in virtual environments. The questionnaire consists of three subscales: involvement (propensity to get involved with an activity), focus (ability to concentrate on enjoyable activities), and games (how much they play games and whether they become involved enough to feel like they are inside the game). These questions were included because the sense of presence within a virtual environment can affect task performance within that environment (Witmer and Singer, 1998).

- **Wayfinding Anxiety.** We measured each participant's trait anxiety and tendency to use a "route-learning" strategy or an "orientation" strategy using Lawton and Kallai's (Lawton and Kallai, 2002) International Wayfinding Anxiety Scale and International Wayfinding Strategy Scale, respectively. These questions were included because wayfinding anxiety can affect navigation performance (Lin et al., 2019), and different strategy use (e.g., a reliance on landmarks or a tendency to navigate using cardinal directions) can affect wayfinding efficiency (Hund and Minarik, 2006).

Route-finding performance was measured in two ways:

- **Completion Time**. The system recorded each participant's total time to complete the eight training routes, the four transfer routes, and the eight retention routes (Study 2 only). The maximum time per route was 90 seconds.

- **Distance Travelled**. The system recorded the total 3D Euclidean distance travelled by the participant for each route (using Unity's default measuring system). A greater distance indicates that the participant made more errors while navigating.

Subjective experience was measured after completing each day's training, and again after the transfer session. These questions relate to RQ1:

- **NASA Task-Load Index (TLX)** (Hart and Staveland, 1988). The NASA Task-Load Index questionnaire is a widely-used (MacKenzie, 2012) questionnaire to rate perceived workload when completing a task. We used the questionnaire's mental demand, performance, effort, and frustration questions.

- **Perceived Map Knowledge**. To measure each participant's perceived map knowledge after training, we asked them to rate their knowledge of the layout of the map, on a 5-point scale from "very poor" to "very good".

3.5.2. Study 2

Study 2 also measured individual differences. The **Immersive Tendencies** and **Wayfinding Anxiety** questionnaires were the same as what was used in Study 1, but other questionnaires were added or revised:

- **Experience with First-Person 3D Games.** Our gaming expertise questions from Study 1 were expanded into a scale with 5 questions. The scale used a 5-point Likert scale from "Not at all" to "Extremely", and the questions included: "Are you a gamer?", "Are you experienced at playing video games?", "Are you experienced with using keyboard and mouse input simultaneously to control games?", "Are you familiar with navigating 3D virtual environments?", and "Are you experienced at playing first-person shooter games?".

- **Spatial Ability.** We also included the Spatial Ability Self-Report Scale (Turgut, 2014). This consists of three sub-scales: Object-Manipulation Spatial Ability (OMSA), Spatial Navigation Ability (SNA), and Visual Memory (VM). Object-Manipulation Spatial Ability involves the ability to mentally rotate or fold objects and the ability to visualize spatial relationships. Spatial Navigation Ability involves the ability to form a mental map of the environment and navigate within it. Visual Memory involves the ability to notice and remember differences in visual stimuli. These questions relate to participants' ability to develop spatial understanding of the environment (RQ2).

- **Intrinsic Motivation.** We used the Intrinsic Motivation Inventory (IMI) (McAuley et al., 1989) to evaluate participants' intrinsic motivation toward the tasks. This inventory measures four dimensions: Interest-Enjoyment, Perceived Competence, Effort-Importance, and Tension-Pressure. These were included because intrinsic motivation toward the task may affect one's interest in continuing to engage with the task. These questions relate to RQ1.

Additionally, we prompted users to answer questions relating to any strategies they used to help them learn about their surroundings:

- "Did you make use of any intentional strategies to remember the specific routes you had trained on previously? ('Yes' or 'No')"

Measure	Question
Map Knowledge	How would you rate your knowledge of the layout of the map? ("Very poor" to "Very good")
Mental Demand	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, forgiving or exacting?
Temporal Demand	How much time pressure did you feel due to the rate at which the task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Peformance	How successful do you think you were in accomplishing the goals of the task set by the experiment (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?
Interest-Enjoyment	I enjoyed this game very much.
Interest-Enjoyment	Playing the game was fun.
Interest-Enjoyment	I would describe this game as very interesting.
Interest-Enjoyment	While playing the game, I was thinking about how much I enjoyed it.
Interest-Enjoyment	This game did not hold my attention.
Perceived Competence	I think I am pretty good at this game.
Perceived Competence	I am satisfied with my performance at this game.
Perceived Competence	After playing the game for a while, I felt pretty competent.
Perceived Competence	I am pretty skilled at the game.
Perceived Competence	I couldn't play this game very well.
Effort-Importance	I put a lot of effort into this game.
Effort-Importance	It was important to me to do well at this game.
Effort-Importance	I tried very hard while playing the game.
Effort-Importance	I didn't try very hard at playing the game.
Tension-Pressure	I felt tense while playing the game.
Tension-Pressure	I felt pressured while playing the game.
Tension-Pressure	I was anxious while playing the game.
Tension-Pressure	I was very relaxed while playing the game.

Table 1: All questions relating to subjective experience used within the two studies. Questions relating to mental demand, temporal demand, performance, effort, and frustration come from the NASA-TLX (Hart and Staveland, 1988). Questions relating to interest-enjoyment, perceived competence, effort-importance, and tension-pressure come from the IMI (McAuley et al., 1989).

- "Did you make use of any intentional strategies to remember the locations of the landmarks? ('Yes' or 'No')"

3.6. Participants

In both studies, participants were recruited through Amazon's Mechanical Turk (MTurk) crowdsourcing platform. MTurk connects willing workers to paid Human Intelligence Tasks (HITs). Ethical approval for the studies was obtained from the behavioural ethics board of the University of Saskatchewan, and participants were asked to renew their consent at the start of each day's task. To comply with ethical guidelines, the task was only available to workers from the United States who were over 18 years old.

3.6.1. Study 1

Participants were first recruited through a HIT limited to 100 people that involved completing a simple navigation task presented as a tutorial and filling out a demographics questionnaire. The task took 5.5 minutes on average (SD=2.1) and paid $0.50 USD.

During the tutorial task, the participant's in-environment framerate was logged and they were asked about their prior experience with our chosen virtual environment. To be eligible for the study, participants needed to be "not at all" or only "slightly" experienced with the Gold Rush environment and our chosen game. Additionally, they needed to have had a framerate higher than 45 frames per second, otherwise, their system may not have performed adequately during the navigation tasks in the study.

We invited back 73 people to complete the full study, with only 50 spots available. On the first day, participants were randomly assigned to one of the three assistance groups, completed initial questionnaires, and a sixteen-route[3] training session. Participants were paid \$3.50 USD for completing the first day, which took 21.7 minutes on average (SD=8.1). The second day consisted only of the same sixteen-route training session, and participants were paid \$3 USD and it took 14.8 minutes on average (SD=10.0). The final day consisted of the final sixteen-route training session and the eight-route transfer session. Participants were paid \$4.50 USD for day three, which took 30.0 minutes on average (SD=10.2).

Of the 50 who started the multi-day study, 46 completed all three days. We excluded two participants from our analysis due to logging errors, leaving us with 44 participants (29 male, 15 female, mean age of 33.7, SD=8.68; min=20; max=59). All participants were randomly assigned to one of the three assistance groups, balancing for self-declared gender: 14 people (5 female, 9 male) received map assistance, 16 people (6 female, 10 male) received position assistance, and 14 people (4 female, 10 male) received trail assistance.

3.6.2. Study 2

Participants were recruited in a slightly different way in Study 2; eligibility was determined by having participants first complete a very brief qualification HIT to confirm that they had little to no experience with the game we selected. A total of 500 participants completed this HIT, which asked three questions and paid \$0.05 USD. Two of the three questions were used to mask our intention, which was to only invite back participants who indicated that they have "no experience" with playing *Wolfenstein: Enemy Territory*, the game that our 3D environment comes from.

Based on the qualification HIT, we invited back participants to complete the full 6-day study. 136 participants completed the first day of the study, which paid \$4 USD and took 21.0 minutes on average (SD=8.9), with 88 of these also completing the next three days of training, which each paid \$2 USD and took 10.2 minutes on average (SD=6.2) and the transfer day, which paid \$2 USD and took 10.0 minutes on average (SD=6.5). Of those, 78 completed the retention day as well, which paid \$3 USD and took 15.8 minutes on average (SD=10.3). Eight participants were removed from the analyses due to a low framerate during the task (less than 30 frames per second). This left 80 participants who completed the training and transfer task and 70 participants who completed all tasks including the retention task.

Due to some participants dropping out of the experiment over the multiple days, we were left with an unequal distribution of participants in assistance groups. For the 80 participants that completed everything except for the retention task, 24 received no assistance (10 female, 14 male), 28 received trail assistance (15 female, 13 male), and 27 received rail assistance (12 female, 15 male). The average age of the participants was 38 years (Min 22, Max 70, SD 10.7). Of the 70 participants that completed every task, 22 received No assistance (9 female, 13 male), 24 received trail assistance (13 female, 11 male), and 24 received rail assistance (10 female, 14 male). The average age was 37.8 (Min=22, Max=70, SD=10.8). There were no non-binary participants.

[3] Eight of the training routes were for a game environment not presented in this work, but in a prior publication. Similarly, four of the transfer routes are not presented here.

3.7. Data Analyses

3.7.1. Study 1

To explore differences in training due to assistance, we performed separate repeated-measures analysis of covariance (RM-ANCOVA) tests for each of our outcome measures (completion time, distance travelled, task-load index, and perceived map knowledge). The day of the training session (1, 2, and 3) was used as the within-subjects factor, and assistance type was used as the between-subjects factor. For the transfer session, separate ANCOVA tests were used for the same outcome measures (no within-subject factor was used).

Individual differences between participants in terms of navigation anxiety, wayfinding strategies, gaming expertise, and immersive tendencies were considered as potential covariates for our statistical tests, based on whether those traits significantly correlated with the dependent measures. For the performance measures, the following covariates were included: ITQ's games subscale, wayfinding anxiety, wayfinding orientation strategy, and gaming expertise. For the subjective measures, the following covariates were included: involvement, wayfinding anxiety, and gaming expertise. Questions are shown in Table 1.

The individual differences measures were also used to verify that there were no differences between the groups as a result of random assignment. One-way ANOVAs with these measures as dependent variables showed no significant differences between the assistance groups. Alpha was set at 0.05, all covariates were mean-centred (Breukelen and Dijk, 2007; Schneider et al., 2015), degrees of freedom for within-subject effects were corrected with Huynh-Feldt estimates of sphericity (Field and Hole, 2002). We performed post-hoc pairwise comparisons following each of the RM-ANCOVAs for the training session's outcome measures and following each ANCOVA for the transfer session's outcome measures. All effect sizes were estimated using partial eta squared.

3.7.2. Study 2

For our measures of performance (Completion Time and Distance Travelled), we used separate RM-ANCOVAs for the Training session, with Day as a within-subjects factor and Assistance as a between-subjects factor. For these measures during our Transfer and Retention sessions, we used separate ANCOVAs.

For the measures of subjective experience, measurements from each day of the Training session were included in separate RM-ANCOVAs (one for each measure) and we report results of the between-subject effects only. Additionally, we used separate ANCOVAs for each subjective measure for the Transfer and Retention sessions.

Individual differences between participants (adding object manipulation ability, spatial navigation ability, and visual memory in addition to those used in Study 1) were considered as potential covariates for our statistical tests, based on whether those traits significantly correlated with the dependent measures. For the performance measures, we used the following covariates: Gaming Experience, Games (from ITQ), and Visual Memory. For the subjective experience measures, we used Gaming Experience, Involvement, Games (from ITQ), Focus, Wayfinding Anxiety, Orientation Strategy, Visual Memory, Object Manipulation, and Spatial Navigation as covariates.

The individual differences measures were additionally used to verify that there were no differences between the groups as a result of random assignment. One-way ANOVAs with these measures as dependent variables showed no significant differences between the assistance groups. Alpha was set at 0.05, all covariates were mean-centred (Breukelen and Dijk, 2007; Schneider et al., 2015), degrees of freedom for within-subject effects were corrected with Huynh-Feldt estimates of sphericity (Field and Hole, 2002). We performed post-hoc pairwise comparisons following each of the RM-ANCOVAs for the training session's outcome measures and following each ANCOVA for the transfer and retention session's outcome measures. All effect sizes were estimated using partial eta squared.

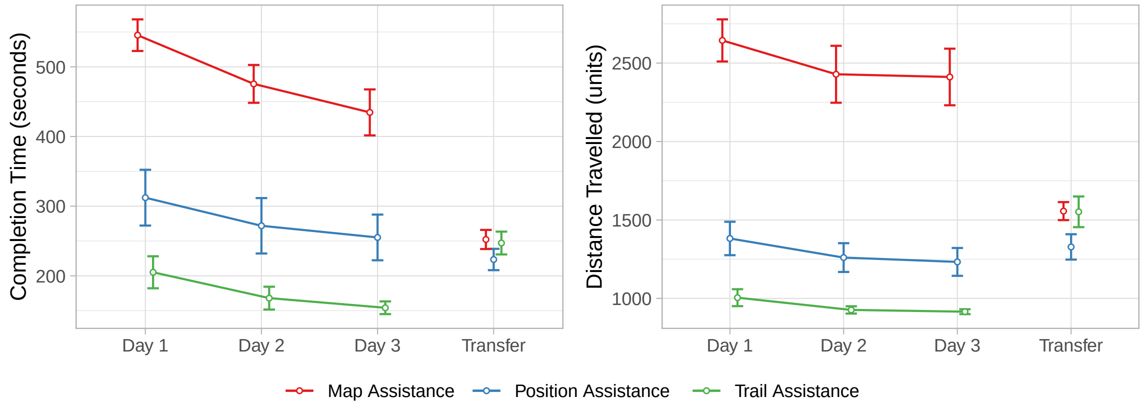


Figure 12: Performance during Training and Transfer sessions for Study 1. Error bars show standard error.

4. Results

4.1. Study 1

4.1.1. Training Tasks: Did Assistance Improve Navigation Performance? (RQ1)

We expected that navigation assistance would help participants' performance when it was present during the Training session, and this is what we found. There was a significant main effect of Assistance on Completion Time ($p < .001$; see Figure 12 for descriptive results and Table 3 for the results of our statistical analyses). Pairwise comparisons showed that the Map group performed worse than the Position and Trail groups (both $p < .001$), but the Position and Trail groups did not show a difference ($p = .149$). The differences were large: participants in the Map condition took approximately 210 seconds longer to complete the routes on average each day compared to the Position participants, and approximately 275 seconds longer than the Trail group. The results were similar for Distance Travelled: there was a significant main effect of Assistance ($p < .001$), and pairwise comparisons showed that the Map group travelled further than either the Position group (1200 units more, $p < .001$) or the Trail group (1500 units more, $p < .001$).

4.1.2. Training Tasks: Did Assistance Improve Subjective Experience? (RQ1)

During Training, with Assistance present, we found significant main effects of Assistance (see Table 3 for full the results of our statistical analyses, and Figure 13 for descriptive results) on Effort ($p = .006$), Frustration ($p < .001$), Perceived Performance ($p < .001$), and Mental Demand ($p < .001$), but not Perceived Map Knowledge ($p = .056$). Introducing Position or Trail assistance led to reductions in Frustration ($p < .001$) and Mental Demand ($p < .001$), and an increase in Perceived Performance ($p \geq .029$) over just Map assistance. Introducing Trail assistance led to a reduction of effort compared to just Map assistance ($p = .007$) but not compared to Position assistance ($p = .060$). There was little subjective difference between Position and Trail assistance; only a reduction in Mental Demand ($p = .009$).

		Study 1				Study 2			
Within-Subject Effect	Measure	*df*	*F*	*p*	η_p^2	*df*	*F*	*p*	η_p^2
Day	Completion Time	**1.70, 62.9**	**18.4**	**<.001**	**.332**	**2.88, 209.9**	**14.5**	**<.001**	**.166**
	Distance Travelled	**1.73, 63.9**	**3.76**	**.034**	**.092**	**2.43, 157.9**	**7.455**	**<.001**	**.103**
Day * Assistance	Completion Time	3.40, 62.9	1.11	.355	.057	**5.75, 209.9**	**5.09**	**<.001**	**.112**
	Distance Travelled	3.45, 63.9	0.23	.901	.012	**4.86, 157.9**	**5.15**	**<.001**	**.137**

Table 2: Within-subjects effects for the RM-ANCOVAs for performance measures for the Training sessions from Study 1 and 2.

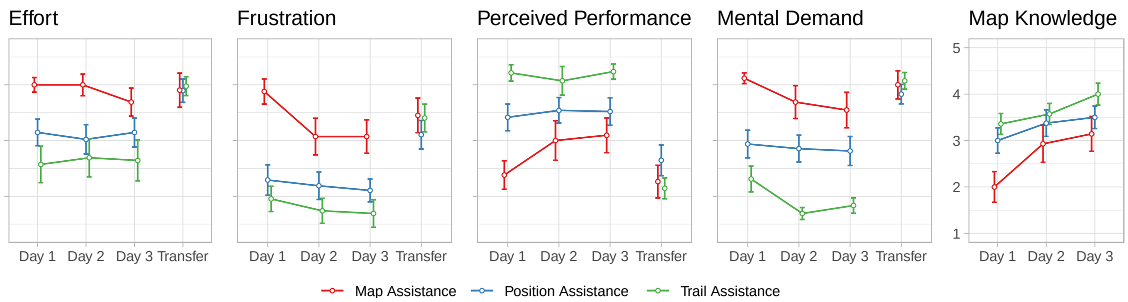


Figure 13: Descriptive results for the measures of subjective experience for Study 1.

4.1.3. Training Tasks: Did Participants Improve Over Time? (RQ2)

For some of our experimental conditions, the degree to which performance improves over time can be considered an approximate measure of spatial learning during the study. If performance did not improve across the days of the study, it may be an indication that the assist was playing a primary role in performance, rather than the participant's spatial knowledge. We note, however, that in the Trail condition, any change in performance may be reduced because navigation was tightly constrained by the assistance.

There was a main effect of Day on Completion Time for the training routes ($p < .001$; see Figure 12 and Table 2). Pairwise comparisons showed that there were significant improvements to Completion Time between Day 1 and 2 ($p < .001$), as well as Day 1 and 3 ($p < .001$), but not between Day 2 and 3 ($p = .064$). This improvement in Completion Time over the days was not affected by Assistance; there was no significant interaction between Day and Assistance.

We found similar results for Distance Travelled. There was a significant effect of Day on Completion Time ($p = .034$). No pairwise comparisons between Days were significant ($p \geq .105$). There was no significant interaction between Day and Assistance.

4.1.4. Transfer Phase: Was Performance or Experience Reduced with the Assist Removed? (RQ2)

Training with assistance could negatively affect the participants' ability to navigate the environment without assistance, but this was not the case in the study. Although we did find a significant main effect of Assistance on Completion Time for the Transfer session ($p = .037$; see Table 3), pairwise comparisons showed that the only significant difference was between Position and Trail assistance ($p = .039$). Results for Distance Travelled were similar, with a significant main effect of Assistance ($p.019$) and a significant pairwise comparison between Position and Trail ($p = .026$). We

		Main Effect of Assistance				Pairwise Comparisons ($p)		
Session	Study 1 Measure	*df*	*F*	*p*	η_p^2	Map - Position	Map - Trail	Position - Trail
Training	Completion Time	**2, 37**	**39.3**	**<.001**	**.680**	**<.001**	**<.001**	.149
	Distance Travelled	**2, 37**	**75.4**	**<.001**	**.803**	**<.001**	**<.001**	.113
	Effort	**2, 38**	**5.80**	**.006**	**.234**	.060	**.007**	.996
	Frustration	**2, 38**	**14.2**	**<.001**	**.428**	**<.001**	**<.001**	>.999
	Perceived Performance	**2, 38**	**9.75**	**<.001**	**.339**	**.029**	**<.001**	.232
	Mental Demand	**2, 38**	**24.6**	**<.001**	**.565**	**<.001**	**<.001**	**.009**
	Perceived Map Knowledge	2, 38	3.12	.056	.141	n/a	n/a	n/a
Transfer	Completion Time	**2, 37**	**3.61**	**.037**	**.163**	.248	>.999	**.039**
	Distance Travelled	**2, 37**	**4.40**	**.019**	**.192**	.100	>.999	**.026**
	Effort	2, 38	0.05	.954	.002	n/a	n/a	n/a
	Frustration	2, 38	0.84	.439	.042	n/a	n/a	n/a
	Perceived Performance	2, 38	1.91	.162	.091	n/a	n/a	n/a
	Mental Demand	2, 38	0.66	.524	.033	n/a	n/a	n/a

Table 3: Between-subjects effects for the RM-ANCOVAs for Study 1's Training session and ANCOVAs for the Transfer session. Each line represents a separate RM-ANCOVA (for the training session) or ANCOVA (for the transfer session).

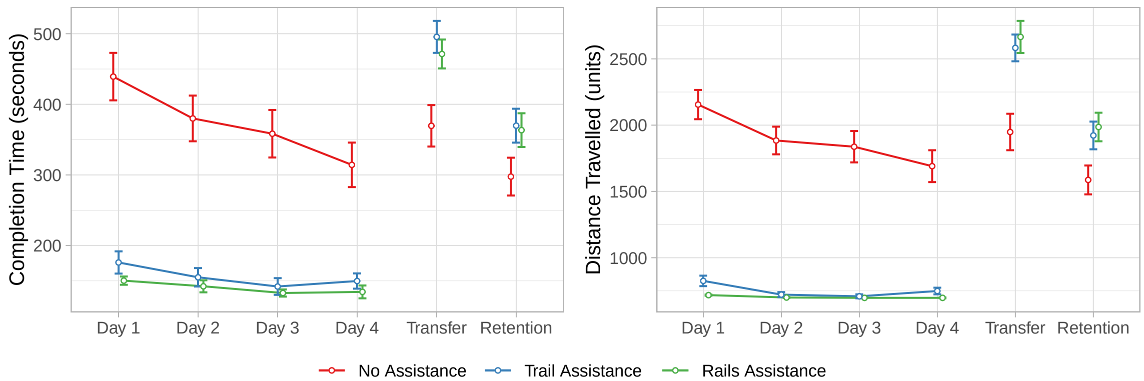


Figure 14: Performance during Training, Transfer and Retention sessions for Study 2. Error bars show standard error.

found no differences between the assistance conditions that required the most effort (Map assist) and the least effort (Trail assist), for either time or distance.

We also asked participants to complete the subjective experience questions after the Transfer tasks. We found no significant main effects of Assistance on Effort, Frustration, Perceived Performance or Mental Demand ($p \geq .162$).

4.2. Study 2

4.2.1. Training Tasks: Did Assistance Improve Navigation Performance? (RQ1)

As in Study 1, we expected that navigation assistance would help participants when it was present (during Training). We found that Assistance reduced Completion Time and Distance Travelled (both $p < .001$; see Figure 14 and Table 4). Post-hoc tests showed that for both measures, there were significant reductions comparing Trail to No assistance ($p < .001$) and when comparing Rail to No assistance ($p < .001$). In both cases, the differences were large — participants in the No assistance condition took more than 220 seconds longer to complete the training routes on average each day and travelled 1100 units more, than either Trail or Rail participants. There were no differences between Trail and Rail assistance ($p > .999$).

4.2.2. Training Tasks: Did Assistance Improve Subjective Experience? (RQ1)

During Training, we found significant main effects of Assistance (see Table 4 for the results of our statistical analyses and Figure 15 for descriptive results) for Effort ($p = .004$), Frustration ($p = .004$), Perceived Performance ($p = .006$), Mental Demand ($p = .021$), Perceived Competence ($p = .015$), and Tension-Pressure ($p = .018$). Pairwise comparisons showed no differences between Trail and Rail assistance ($p \geq .811$). However, we find that when comparing to No Assistance, Trail assistance reduces Effort ($p = .012$), Frustration ($p = .015$), and Mental Demand ($p = .034$), while increasing Perceived Performance ($p = .021$). Comparing No assistance to Rail assistance, we find reductions in Effort ($p = .009$), Frustration ($p = .007$), Tension-Pressure ($p = .021$), and increases in Perceived Performance ($p == .009$) and Competence ($p = .021$).

4.2.3. Training Tasks: Did Participants Improve Over Time? (RQ2)

As in Study 1, we considered whether participants were learning the environment and improving over their task time during training. In Study 2, both the Trail and Rail conditions strongly dictate completion time (in Rails, for example, task times will always be the same if the participant presses and holds the W key), and so we only expected to see learning effects in the No assistance condition.

Session	Study 2 Measure	Main Effect of Assistance				Pairwise Comparisons (p)		
		df	F	p	η_p^2	No - Trail	No - Rail	Trail - Rail
Training	Completion Time	**2, 73**	**62.7**	**<.001**	**.632**	**<.001**	**<.001**	>.999
	Distance Travelled	**2, 65**	**209**	**<.001**	**.866**	**<.001**	**<.001**	>.999
	Effort	**2, 77**	**5.95**	**.004**	**.134**	**.012**	**.009**	>.999
	Frustration	**2, 77**	**5.92**	**.004**	**.133**	**.015**	**.007**	>.999
	Perceived Performance	**2, 77**	**5.56**	**.006**	**.126**	**.021**	**.009**	>.999
	Mental Demand	**2, 77**	**4.05**	**.021**	**.096**	**.034**	.058	>.999
	Perceived Map Knowledge	2, 77	1.62	.205	.040	n/a	n/a	n/a
	Interest-Enjoyment	2, 77	0.32	.729	.008	n/a	n/a	n/a
	Perceived Competence	**2, 77**	**4.47**	**.015**	**.104**	.170	**.012**	.811
	Effort-Importance	2, 77	1.93	.152	.048	n/a	n/a	n/a
	Tension-Pressure	**2, 77**	**4.21**	**.018**	**.098**	.089	**.021**	>.999
Transfer	Completion Time	**2, 74**	**9.01**	**<.001**	**.196**	**<.001**	**.013**	.672
	Distance Travelled	**2, 72**	**9.12**	**<.001**	**.202**	**.002**	**<.001**	>.999
	Effort	**2, 68**	**5.21**	**.008**	**.133**	.207	**.006**	.502
	Frustration	**2, 68**	**6.31**	**.003**	**.157**	**.005**	**.016**	>.999
	Perceived Performance	**2, 68**	**12.0**	**<.001**	**.261**	**<.001**	**<.001**	>.999
	Mental Demand	**2, 68**	**6.38**	**.003**	**.158**	**.023**	**.004**	>.999
	Perceived Map Knowledge	**2, 68**	**17.3**	**.008**	**.338**	**<.001**	**.002**	.100
	Interest-Enjoyment	2, 68	0.18	.836	.005	n/a	n/a	n/a
	Perceived Competence	**2, 68**	**14.5**	**<.001**	**.299**	**<.001**	**<.001**	>.999
	Effort-Importance	2, 68	1.33	.270	.038	n/a	n/a	n/a
	Tension-Pressure	**2, 68**	**8.35**	**.001**	**.197**	**.003**	**.001**	>.999
Retention	Completion Time	2, 65	2.72	.073	.077	n/a	n/a	n/a
	Distance Travelled	**2, 63**	**3.32**	**.042**	**.095**	.258	**.041**	>.999
	Effort	**2, 59**	**7.12**	**.002**	**.194**	**.029**	**.002**	>.999
	Frustration	2, 59	1.73	.186	.055	n/a	n/a	n/a
	Perceived Performance	**2, 59**	**3.75**	**.029**	**.113**	.077	**.053**	>.999
	Mental Demand	**2, 59**	**6.86**	**.002**	**.189**	.300	**.001**	.147
	Perceived Map Knowledge	**2, 59**	**5.32**	**.008**	**.153**	**.014**	**.029**	>.999
	Interest-Enjoyment	2, 59	2.02	.142	.064	n/a	n/a	n/a
	Perceived Competence	2, 59	2.17	.124	.068	n/a	n/a	n/a
	Effort-Importance	2, 59	2.24	.115	.071	n/a	n/a	n/a
	Tension-Pressure	**2, 59**	**3.63**	**.033**	**.109**	.454	**.028**	.673

Table 4: Between-subjects effects for the RM-ANCOVAs for Study 1's Training session and ANCOVAs for the Transfer and Retention sessions. Each line represents a separate RM-ANCOVA (for the training session) or ANCOVA (for the transfer and retention sessions).

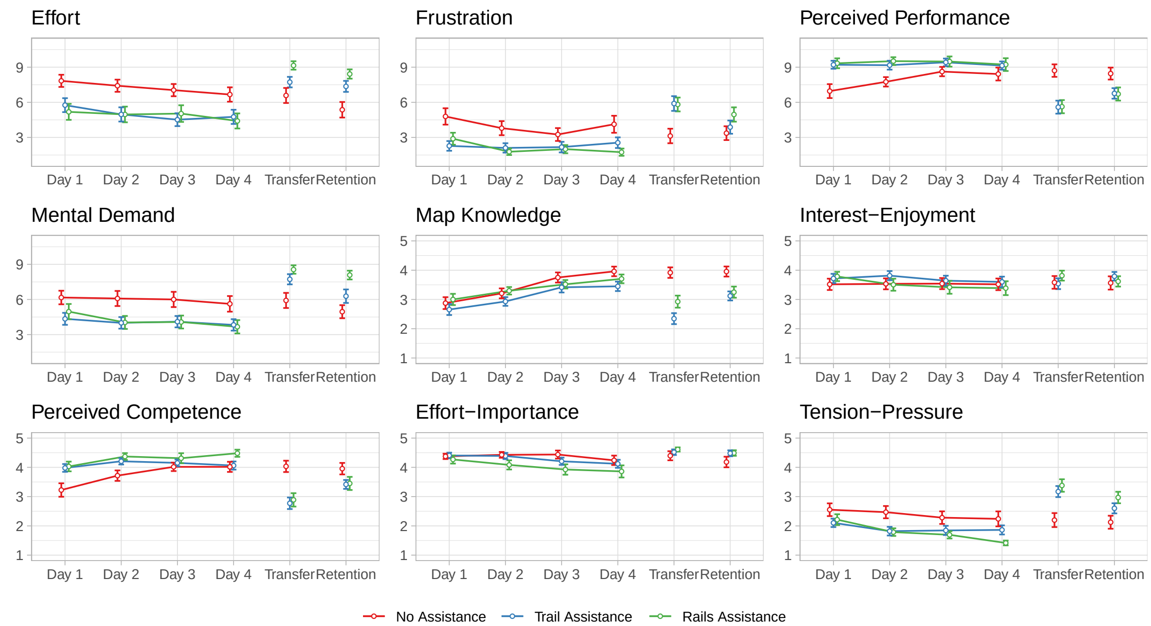


Figure 15: Descriptive results for the measures of subjective experience for Study 2.

We found that participants did improve over time, but that the amount of improvement depended on the assistance. There was a significant interaction between Day and Assistance for Completion Time and Distance Travelled ($p < .001$ for both; see Table 2).

To determine which of the groups were improving during training, we examined the pairwise comparisons to compare Day 1 and Day 4 performance for each Assistance group. For Completion Time, we found that the No assistance group improved over the training phase ($p < .001$), but Trails and Rails did not (both $p > .999$). For Distance travelled, results were similar: the No assistance group improved ($p < .001$), but the Trails and Rails groups did not ($p > .999$).

4.2.4. Transfer and Retention Tasks: Was Performance or Experience Reduced with the Assist Removed? (RQ2)

The effect of assistance on spatial learning was inferred by measuring performance in the Transfer and Retention tasks. On the Transfer task, where assistance was removed and participants were asked to navigate new routes, we found a significant main effect of Assistance on Completion Time and Distance Travelled ($p < .001$ for both; see Table 4). Post-hoc tests show that there were significant increases in Completion Time and Distance Travelled when comparing Trail to No assistance ($p \leq .002$), as well as when comparing Rail to No assistance ($p \leq .013$), but not when comparing Trail and Rail assistance ($p \geq .672$).

On the Retention task (also without assistance but on the routes participants had previously practiced during training), we did not find a significant main effect of Assistance on Completion Time ($p = .073$), but we did find an effect of Distance Travelled ($p = .042$; see Table 4). Post-hoc tests for Distance Travelled show only a difference between No assistance and Rail assistance ($p = .041$, $p \geq .258$ for the others), with the No assistance group travelling a shorter distance.

For subjective experience measures taken after the Transfer session, we found significant main effects of Assistance (see Table 4) for Effort ($p = .008$), Frustration ($p = .003$), Perceived Performance ($p < .001$), Mental Demand ($p = .003$), Perceived Map Knowledge ($p = .008$), Perceived Competence ($p < .001$), and Tension-Pressure ($p = .001$). As in Training, pairwise comparisons showed no differences between having trained with Rail assistance to having trained with Trail assistance ($p \geq .100$). When comparing No assistance to Trail assistance, we find increased Frustration ($p = .005$), Mental Demand ($p = .023$), Tension-Pressure ($p = .003$), along with decreased Perceived Performance ($p < .001$), Map Knowledge ($p < .001$), and Competence ($p < .001$). Comparing No assistance to Rail assistance, we find increased Effort ($p = .006$), Frustration ($p = .016$), Mental Demand ($p = .004$), and Tension-Pressure ($p = .001$), as well as decreased Perceived Performance ($p < .001$), Map Knowledge ($p = .002$), and Competence ($p < .001$).

After the Retention session, we found significant main effects of Assistance (see Table 4) for Effort (p), Perceived Performance ($p = .029$), Mental Demand ($p = .002$), Perceived Map Knowledge ($p = .008$), and Tension-Pressure ($p = .033$). Pairwise comparisons showed no differences between Rail and Trail assistance ($p \geq .147$). Comparing No assistance to Trail assistance, we find increased Effort ($p = .029$) and decreased Perceived Map Knowledge ($p = .014$). Comparing No assistance to Rail assistance, we find increased Effort ($p = .002$) and Mental Demand ($p = .001$) and decreased Perceived Map Knowledge ($p = .029$).

4.2.5. Did Participants Make Use of Intentional Strategies? (RQ2)

The differing level of effort for the three assistance techniques may have prompted users to employ different strategies for navigation. Based on questionnaire responses, we found that 35% of participants made use of intentional strategies to remember the locations of landmarks, and 22.5% used strategies to remember the routes taken. Comparing between the groups, participants in the No-assistance group were less likely to report using strategies for routes (16.7% for No assistance, 27.6% for Trail, and 22.2% for Rail). This pattern was reversed, however, for remembering landmarks (41.7% for No assistance, 34.5% for Trail, and 30% for Rail).

5. Discussion

5.1. Summary of Results

Our studies explored two research questions: first, will navigation assistance improve performance and user experience when it is present? and second, will navigation assistance hinder spatial learning and cause over-reliance on the assist? We investigated the first question by having participants undergo training with one of three levels of assistance (different levels were used in each study). In Study 1, we found that higher levels of navigation assistance (marking the user's position on a map or displaying a glowing trail to the destination) led to significant performance improvements compared to a map alone, both in terms of completion time and distance travelled — although there was little difference between the low-effort Trails condition and the medium-effort Position condition. In Study 2, which used assistance techniques with a wider range of requirements for navigation effort, we found a similar result. In training, the No assistance group performed significantly worse than either Trail or Rail assistance in terms of completion time and distance travelled (the two lowest-effort conditions, Trail and Rail assistance, performed similarly). Both studies also showed the benefit of navigation assistance on user experience. Study 1 showed reduced effort, frustration, and mental demand, as well as an increase in perceived performance, for both of the lower-effort conditions (Position and Trail) compared to the Map condition. Study 2 showed reduced frustration, mental demand, effort, and tension, as well as an increase in perceived competence and performance, for the lower-effort conditions (Trail and Rail) compared to the No-assist condition.

We investigated the second research question by having participants navigate the same environment again, but without assistance — completing transfer tasks (with new routes) and retention tasks (with the same routes as in training). In the transfer test of Study 1, we found that the performance of all three groups was similar once the assistance was removed. Although there was a difference between Position and Trail assistance, there were no significant differences between the least-effortful condition (Trail assistance) and the most-effortful condition (Map assistance). In Study 2 we carried out both a transfer test and a retention test. In transfer tasks (and unlike Study 1) we found that the No-assist group performed significantly better in terms of both completion time and distance travelled, with the two lower-effort techniques performing similarly. Experience measures were also reversed compared to Study 1, with the No-assist condition rated better than either the Trail or Rail conditions. In retention tasks, we found no significant difference in completion time regardless of which assistance participants had seen in training, but we did find an effect on distance travelled (participants who trained with no assistance travelled less during the retention tasks). Removing the assist in the transfer tasks also led to different effects on user experience, depending on the study. In Study 1, there were no differences between the conditions in the transfer task. In Study 2, removing the Trail and Rail assistance in the transfer tasks led to significantly lower scores on experiential measures compared to the No-assist condition (which was the same between training and transfer phases); similar results were found for the retention tests.

5.2. Explanation of Results

5.2.1. Why did Map assistance not result in better learning?

In Study 1's transfer test, where navigation assistance was taken away, we observed that the least-assisted group (Map assistance) performed similarly to the most-assisted group (Trail assistance), even though users had to expend considerably more effort when they only had a map. We propose two possibilities for why this occurred.

One possibility is that incidental learning took place during training, allowing players to learn the environment regardless of the amount of effort they invested (as suggested by previous researchers (Andrade and Meudell, 1993; Hasher and Zacks, 1979)). Incidental learning may have occurred because participants were still observing their surroundings during training, and this may have helped them remember enough to navigate later on. In both the Position and Trail conditions, we believe that it is important that participants actively participated in traversing the route — if they had not had this experience (e.g., if the assist had teleported them directly to their destination), their ability to learn the environment incidentally would be greatly reduced.

Another possibility is that the Map condition did not do a good job of scaffolding spatial learning, even though it required more effort than the other conditions. For example, if translating back and forth from the map to the first-person view was confusing for participants, it may have induced an incorrect mental model that led to participants becoming so lost that they were unable to learn the environment, despite the extra effort. However, we believe that this explanation is unlikely given that most participants in the Map-assist condition were able to complete the routes, and found at least some of the landmarks during the transfer task. Considering how much additional time the Map-assist participants spent in training (a total of 23.8 minutes across the three days, compared to 10 minutes for Trail assistance), it is surprising that they did not perform better than the other conditions on the transfer test.

To avoid the potential problem of users becoming so lost that they are unable to learn anything, Study 2 slightly modified the 3D environment to block off two sections of the map that did not have clear landmarks. Study 2 also removed the Map-assist condition, and instead used a No-assist setup as the lowest level of assistance (and the highest level of effort). The No-assist group showed the largest difference compared to the lower-effort techniques once assistance was removed, and it may be that training with no assist at all provides some benefit to learning. Participants in the No-assist condition of Study 2 took about the same time to complete training routes as people in the Map-assist condition of Study 1 — and although the routes in Study 2 were easier due to the modified environment, it is possible that the single consistent representation of the No-assist condition was better than two competing representations of Map-assist. Future work should consider whether an assist such as a basic map could be detrimental to learning, perhaps because of the added cost of translating back and forth between representations of the environment (Khan and Rahman, 2017).

5.2.2. Why did Position assistance result in greater learning than Map and Trail assistance?

In Study 1, we observed that the Position assistance group performed the best in testing, significantly outperforming the group that trained with Trail assistance, and also having a lower mean than the Map-assist group (although this difference was not significant). Based on the positive results from the No-assist condition in Study 2 (see discussion above), it is possible that participants in the Map assistance group were unable to properly make use of the map to navigate through the environment. The Position assist provided the participant's current location on the map, which freed the user from having to identify and track their own location — and this likely made the map more beneficial (or otherwise allowed participants to better parse it). Having a clearer understanding of their own location in the environment may have helped participants in the formation of survey knowledge (as suggested by (Thorndyke and Hayes-Roth, 1982) and (Taylor et al., 1999)) that could be leveraged when finding new routes to landmarks.

5.2.3. Why did Rail assistance not limit learning compared to Trail assistance?

Given the ability of participants in the Trail assistance condition from Study 1 to successfully complete the transfer tasks, we believe that incidental learning can be effective even when navigation effort is low. That is, by passively observing the environment (and without any intentional effort), users can develop spatial knowledge of an environment. Study 2's results provide additional support for this idea — our results showed that participants who simply held down a button to be taken in the correct direction (Rails assistance) were equally capable of navigating the environment as participants who actively engaged with the environment to follow the glowing trail of the Trails condition.

How could this be? First, we felt it was important that participants maintained their attention on the task. Therefore, instead of allowing them to simply watch what went by on the screen, we asked them to hold down a button — if they had not watched what was on screen, there would have been no way for them to learn about the environment. Second, the Rails-style form of assistance has similarities to watching a demonstration, something that has been shown to be beneficial for early learning when considering perceptual-motor skills (Pollock and Lee, 1992; Newell, 1981).

5.2.4. Why weren't the observed differences more pronounced?

Although we did find statistically significant differences between our different assistance groups, when the results are considered from a descriptive perspective, it is rather surprising how small the differences between the groups are in transfer tasks. In Study 1, the Map and Trail assistance groups completed the transfer test within 10 seconds of each other, and the Map group was only 45 seconds faster than the slowest group (in a set of tasks that took about 240 seconds overall). And yet, the Map group spent considerably more total time training within the environment — about 1.8 times that of the Position assistance group and 2.4 times that of the Trail assistance group.

In Study 2's retention test, the Rail and Trail assistance groups performed similarly to the No assistance group's third day of training. This is despite the No-assist group having spent more time practicing within the environment at that point (a total of 13.7 minutes for No assistance after two days, compared to 10.4 and 9.3 minutes after all four days of training for the Trail and Rail assistance groups). Therefore, while training without any assistance does appear to result in better learning, it does not appear to be a time-efficient way for users to learn how to navigate the environment. Overall, No-assist participants spent a total of 24.9 minutes in training across all four days, more than double the training time of Trail and Rail assistance. Even with less than half the training time, assisted participants were still able to navigate the environment competently, even if they weren't able to match the performance of the unassisted participants in the transfer tasks.

Why, then, are the differences between the groups not more pronounced? Previous work on assistance and skill learning (presented in Section 2.1) suggests that learners given assistance will become reliant on the assist and be unable to complete the task if that assistance is taken away. However, this applies primarily to tasks which are relatively simple, such as tasks where the goal is to learn specific stimulus-response pairings (e.g., Singer and Pease, 1976) or reproduce specific movements (e.g., Armstrong, 1970). However, when considering more complex skills, such as reproducing slalom-type movements on a ski simulator, guidance can benefit learning (Wulf et al., 1998).

The learning of perceptual-motor skills often occurs through trial and error (Singer, 1980), where a learner attempts a task and observes the response-produced feedback to evaluate how well they performed that task (Summers, 1989; Schmidt et al., 2018). For simple skills, response-produced feedback is easy to parse. A learner notices their mistakes and adjusts how they are executing the skill (Johnson, 2004). Navigation differs from simple perceptual-motor skills in that it is not always apparent when a mistake has been made (such as taking a wrong turn). The user might simply keep moving forward until they conclude that their destination is not in sight and will not be in sight any time soon — and only then do they realize they have made a mistake sometime in the past. Navigation learning is therefore different from the learning of perceptual-motor skills that rely on trial-and-error learning, and it makes sense that the findings of work looking at those skills may not generalize to navigation learning.

This raises the question of how participants are learning the environment, if not through trial and error. As discussed previously, a likely reason that participants are able to learn how to navigate through the environment is due to incidental learning — the ability to passively acquire spatial knowledge about the environment. We believe it important that navigation assistance systems allow participants to keep their full attention on the game rather than dividing their attention, as might have occurred using other forms of assistance. Trail, Rail, and No assists all allowed participants to give the environment their full attention, while the Map and Position assists may have allowed participants to gain survey knowledge from the map.

5.3. Applying Navigation Assistance to Virtual Environments

In our two studies, we found that navigation assistance provided immediate benefits to participants. In Study 1, navigation assistance also did not affect learning; all participants navigated the environment equally well once assistance was removed. In Study 2, there were some detrimental effects to learning, however, performance gains made by including assistance were substantial, and the detrimental effects on learning were slight, especially when considering just how much time is saved during training by having assistance present. Furthermore, it may be possible to mitigate the detrimental learning effects of assistance by adjusting the presentation and the type of assistance provided to users. The assistance used in our studies covered an extreme range (particularly in Study 2) and there may be ways to get similar benefits while limiting any negative effects on learning.

One might first consider, however, whether there even will be a time when assistance gets removed. It might be that assistance can always be provided to users and that the detrimental effects of removing the assistance will never be experienced. Nonetheless, if there is the possibility that assistance will be removed, it should be possible to mitigate the detrimental effects. One useful approach may be to "fade out" the assistance — an approach that has been shown to be beneficial in the context of assistance for perceptual-motor skills (Singer and Pease, 1976; Winstein et al., 1994). For the glowing-trail assistance, for example, this can be done by literally fading out the path as the participant spends more time in the game. For other types of assistance, similar approaches could be achieved by removing the assistance for some attempts and therefore being presented less often over time. For the rail assistance in particular, we note that a user who is taken along a route and then asked to navigate it on their own is a scenario that closely resembles the rail assistance used in Study 2, and is analogous to taking away one's assistance.

Second, the potentially detrimental effects of assistance are dependent on the assistance, so consideration should be given to the type of assistance presented to users. For making this choice, both studies offer some insights. In Study 2, we saw that Trail assistance and Rail assistance resulted in equal levels of performance. It therefore may make more sense to give the user the autonomy to navigate the world on their own and provide Trail rather than Rail assistance. The Position assistance of Study 1 resulted in similar performance to Trail assistance, so if the system allows the user enough time to pause and review a map, this type of assistance could be used.

5.3.1. Applying Navigation Assistance to Game Navigation

One setting where navigation assistance would be particularly helpful is digital games. In selecting the type of navigation assistance to give a player, game designers should consider the pace of the game and whether knowing which direction to travel will greatly affect a player's performance. For example, Trail assistance is well suited to fast-paced games where navigation errors are detrimental (e.g., in a multiplayer first-person shooter). However, if navigation errors are less of a problem, and if the game affords the player enough time to pause during navigation, then providing the player with a map with Position assistance would provide the player with additional survey knowledge that they could apply later on in the game, while also providing benefits to immediate performance. This approach would be better suited for single-player games with a slower pace (e.g., open-world role-playing games). Aside from the pace of the game, there may be other reasons to include navigation assistance. In particular, navigation assistance may help facilitate social play by allowing a novice player to play with a more skilled friend.

The Rail method was our most extreme form of assistance — are there realistic scenarios in which providing players with this type of guidance makes sense? On the surface, it may seem unlikely that a virtual environment would ever make use of rail-based assistance as it is quite invasive. However, there are many scenarios in games that resemble aspects of our Rail assistance. In particular, rail-like navigation assistance can be found in cut scenes of single-player games; and in multi-player games the concept of watching others play and navigate through the environment is common. This situation comes up fairly often, for example, when watching others play games on platforms such as Twitch or YouTube, or when a player is spectating in-game (e.g., when waiting to respawn in an online team-based first-person shooter). That players can learn the environment through passive observation has interesting implications in terms of designing the experience of learning the game for new players. For example, a new player of a first-person shooter game who dies frequently will be given opportunities to learn the game simply because they will watch others play the game. This time that might have previously been seen as simply waiting to play again actually might be beneficial to the player.

Navigation assistance can also be applied by game designers to aid a player's learning of the game. New players have a lot to learn about a game before they can be successful at it, and providing navigation assistance will aid them in two ways. First, it encourages them to engage in part-task practice (Magill, 2007), in which the player can direct their attention towards learning only specific skills within the game. For example, navigation assistance in an FPS game could free the player to work on the skills of aiming, movement, or monitoring audiovisual cues to detect enemies (Johanson and Mandryk, 2016). Second, it decreases the difficulty of the game, potentially aiding learning by providing them with challenges just at the edge of their capabilities (Vygotsky, 1978), where players feel they are able to overcome them (Juul, 2013) and are motivated to do so (Gee, 2005).

An implementation of navigation assistance in a commercial game could also consider the game state and direct the player's attention toward important objectives. For example, if a player has no weapons or is low on health, the game could show a trail to the nearest weapon or the nearest health pack. A player's role in a team game could also determine which routes are visualized for that player (e.g., a trail to a wounded player for a medic role). Finally, for scenarios in which navigational assistance is not possible, or where the player chooses to turn off the assists (u/CherrySlurpee, 2016; Jul and Furnas, 1997), it appears that the use of even strong assistance early in a player's experience will not significantly affect their long-term performance.

5.4. Limitations and Future Work

A limitation of this work was that the environment we used was from an older (2003) game, and therefore the textures used were of low fidelity and the different parts of the environment were not as visually distinct from one another as they may be in virtual environments within newer games. However, this environment was used because of its ecological validity (it is an environment from a commercially produced game), the availability of the source code from the game, and because it kept the system requirements of the experiment relatively low so that more participants could successfully complete it. Further, it contains multiple alternative routes to reach each landmark. We must acknowledge that if the environment was more visually varied, it is possible that some of our participants' strategies would have been more effective (e.g., trying to remember what the area surrounding each landmark looked like). Therefore, future work should investigate whether our results will hold in different environments with different levels of detail.

An additional limitation is that this experiment was conducted using our online participants' desktop or laptop setups. Therefore, participants completed the task with a variety of displays of different sizes and types. Different displays or devices (such as head-mounted virtual-reality devices) may provide different levels of immersion or require different interfaces to help people navigate virtual environments, limiting the generalizability of our findings.

Our future work will also examine several issues raised by the studies. First, we will examine whether navigation assistance does in fact enable part-task practice that allows players to focus on other skills. Second, we will test navigation assistance in virtual environments with different styles and contents (e.g., a forest, the interior of a large building, or a more dense urban environment). Third, we will explore versions of navigation assistance that gradually disappear, to see if the downsides of abruptly removing assistance can be mitigated. Fourth, we will implement navigation assistance in actual play settings, to see if navigation assistance can improve play experience and game balance. Fifth, we will look further at whether a secondary representation of the environment (such as a map) can actually be a hindrance due to the costs of translating between representations. Sixth, we will further investigate the idea that the strength of the guidance hypothesis may be dependent on the complexity and temporal sequencing of the task. Seventh, we will revise our studies for testing with head-mounted VR displays — this will involve some changes to the different assistance techniques, but the same research questions can be explored.

6. Conclusion

Navigation in 3D virtual environments can be difficult for novices, and this difficulty is something that designers of these environments often want to minimize. We carried out two studies in which we tested the effects of navigation assistance on performance and spatial learning.

Results from Study 1 showed that during training, increasing the level of navigation assistance significantly and substantially improved performance: the Position-assist and Trail-assist conditions were significantly faster than the Map-assist condition, and by a large margin (e.g., for Position assist, a mean of 265 seconds totalled across the 8 routes, and 200 seconds for Trail assist, versus 480 seconds for Map assist). There was no statistical difference between Position-assist and Trail-assist. Results were similar for distance travelled.

In the final tasks with only Map assist, we found no evidence that increased assistance during training led to reduced performance with the assistance removed: in particular, there was no difference in either completion time or distance travelled between the groups who had trained with Position assist or Trail assist and the group who had trained with Map assist. In addition, the performance differences between the three conditions were much smaller in the final task than in training, with the greatest difference between our conditions being only 50 seconds compared to 275 seconds in training.

Overall, Study 1 shows that navigational assistance substantially improves performance for novice users, and suggests that early assistance does not substantially reduce performance when the assist is removed. In addition, even though the Map-assist group spent considerably more time in the virtual environment during training, this additional time did not appear to make them more familiar with the environment than the groups who had navigation assistance.

Study 2's results showed again that navigation assistance significantly and substantially improved navigation during training: mean completion time for the No-assist group was about 375 seconds, but was 155 seconds for Trail and 140 seconds for Rail assists. Similar results were found for distance travelled (mean of 1900 units for No assist vs. 760 units for Trail and 690 units for Rail).

Our wider range of assist conditions in Study 2, however, did show an effect of the navigation assist used in training when considering performance in the transfer tasks (with no assistance). Groups who had trained with either Trail or Rail assist were significantly slower on the transfer tasks (by about 130 seconds for Trail and 110 for Rail) than groups who had trained with No assist. Results were similar for distance travelled (a difference of 650 units for Trail, 770 units for Rail). Unlike Study 1, where there appeared to be no negative effect of providing increased navigation assistance, Study 2 showed that there can be performance detriments if people have an early navigation assist that is subsequently removed. However, it is important to consider the overall balance of benefits to drawbacks — and in Study 2, the increased performance associated with the navigation assist was twice as large as the reduction when the assist was removed (+220 seconds vs -110 seconds for Trail +235 seconds vs -130 seconds for Rail).

Furthermore, the performance detriment appears to diminish over time. On the retention task one week later, we found that those who trained with Trail or Rail were not significantly slower than those who trained without (only by about 60 seconds). Although they were still travelling greater distances, the size of the difference was now smaller (270 seconds and 390 units). If users who had early navigation assistance can quickly catch up with users who had to learn the environment without assistance, then there is a stronger argument for using navigation assistance.

Overall, our studies provide new empirical evidence about how navigation assistance affects performance and spatial learning — and our results imply that designers of 3D environments should strongly consider adding navigation assistance. Assistance provides major benefits both in terms of performance and user experience, and the limited negative effects on spatial learning appear to be considerably outweighed by the benefits for novices.

References

Andrade, J., Meudell, P., 1993. Short report: Is spatial information encoded automatically in memory? The Quarterly Journal of Experimental Psychology Section A 46, 365–375. URL: https://doi.org/10.1080%2F14640749308401051, doi:10.1080/14640749308401051.

Angel Studies, 2000. Midtown Madness 2. Microsoft. Game [PC].

Armstrong, T.R., 1970. Training for the production of memorized movement patterns, in: Proceedings, Scientific and Technical Information Division, National Aeronautics and . . . . p. 449.

van Asselen, M., Fritschy, E., Postma, A., 2005. The influence of intentional and incidental learning on acquiring spatial knowledge during navigation. Psychological Research Psychologische Forschung 70, 151–156. URL: https://doi.org/10.1007%2Fs00426-004-0199-0, doi:10.1007/s00426-004-0199-0.

Bakdash, J.Z., Linkenauger, S.A., Proffitt, D., 2008. Comparing decision-making and control for learning a virtual environment: Backseat drivers learn where they are going. URL: https://doi.org/10.1037%2Fe578342012-007, doi:10.1037/e578342012-007.

Bethesda Game Studios, 2011. The Elder Scrolls V: Skyrim. Bethesda Softworks. Game [PC].

Blizzard Entertainment, 2004. World of Warcraft. Blizzard Entertainment. Game [PC].

Blizzard Entertainment, V., 2021. Diablo II: Resurrected. Blizzard Entertainment. Game [PC].

Breukelen, G.J.V., Dijk, K.R.V., 2007. Use of covariates in randomized controlled trials. Journal of the International Neuropsychological Society 13. URL: https://doi.org/10.1017%2Fs1355617707071147, doi:10.1017/s1355617707071147.

Burigat, S., Chittaro, L., 2007. Navigation in 3d virtual environments: Effects of user experience and location-pointing navigation aids. International Journal of Human-Computer Studies 65, 945–958. URL: https://doi.org/10.1016%2Fj.ijhcs.2007.07.003, doi:10.1016/j.ijhcs.2007.07.003.

Burnett, G.E., Lee, K., 2005. The effect of vehicle navigation systems on the formation of cognitive maps, in: Traffic and Transport Psychology. Elsevier, pp. 407–418. URL: https://doi.org/10.1016%2Fb978-008044379-9%2F50188-6, doi:10.1016/b978-008044379-9/50188-6.

Chase, W.G., 1983. Spatial representations of taxi drivers, in: The Acquisition of Symbolic Skills. Springer US, pp. 391–405. URL: https://doi.org/10.1007%2F978-1-4613-3724-9_43, doi:10.1007/978-1-4613-3724-9_43.

Chen, C.H., Chang, W.C., Chang, W.T., 2009. Gender differences in relation to wayfinding strategies, navigational support design, and wayfinding task difficulty. Journal of Environmental Psychology 29, 220–226. URL: https://doi.org/10.1016%2Fj.jenvp.2008.07.003, doi:10.1016/j.jenvp.2008.07.003.

Chen, J.L., Stanney, K.M., 1999. A theoretical model of wayfinding in virtual environments: Proposed strategies for navigational aiding. Presence: Teleoperators and Virtual Environments 8, 671–685. URL: https://doi.org/10.1162%2F105474699566558, doi:10.1162/105474699566558.

Chrastil, E.R., Warren, W.H., 2011. Active and passive contributions to spatial learning. Psychonomic Bulletin & Review 19, 1–23. URL: https://doi.org/10.3758%2Fs13423-011-0182-x, doi:10.3758/s13423-011-0182-x.

Craik, F.I., Lockhart, R.S., 1972. Levels of processing: A framework for memory research. Journal of Verbal Learning and Verbal Behavior 11, 671–684. URL: https://doi.org/10.1016%2Fs0022-5371%2872%2980001-x, doi:10.1016/s0022-5371(72)80001-x.

Cryptic Studios, 2013. Neverwinter. Perfect World Entertainment. Game [PC].

Darken, R.P., Peterson, B., 2014. Spatial orientation, wayfinding, and representation, in: Handbook of Virtual Environments. CRC Press, pp. 497–522. URL: https://doi.org/10.1201%2Fb17360-28, doi:10.1201/b17360-28.

Darken, R.P., Sibert, J.L., 1993. A toolset for navigation in virtual environments, in: Proceedings of the 6th annual ACM symposium on User interface software and technology - UIST '93, ACM Press. URL: https://doi.org/10.1145%2F168642.168658, doi:10.1145/168642.168658.

Darken, R.P., Sibert, J.L., 1996a. Navigating large virtual spaces. International Journal of Human-Computer Interaction 8, 49–71. URL: https://doi.org/10.1080%2F10447319609526140, doi:10.1080/10447319609526140.

Darken, R.P., Sibert, J.L., 1996b. Wayfinding strategies and behaviors in large virtual worlds, in: Proceedings of the SIGCHI conference on Human factors in computing systems common ground - CHI '96, ACM Press. URL: https://doi.org/10.1145%2F238386.238459, doi:10.1145/238386.238459.

DICE, 2008. Mirror's Edge. Electronic Arts. Game [Xbox 360, PS3].

Dijk, B.V., Akker, R.O.D., Nijholt, A., Zwiers, J., 2003. Navigation assistance in virtual worlds. Informing Science: The International Journal of an Emerging Transdiscipline 6, 115–125. URL: https://doi.org/10.28945%2F519, doi:10.28945/519.

Dubois, H., Callet, P.L., Coutrot, A., 2021. Visualizing navigation difficulties in video game experiences, in: 2021 13th International Conference on Quality of Multimedia Experience (QoMEX), IEEE. URL: https://doi.org/10.1109%2Fqomex51781.2021.9465423, doi:10.1109/qomex51781.2021.9465423.

Ehret, B.D., 2002. Learning where to look, in: Proceedings of the SIGCHI conference on Human factors in computing systems Changing our world, changing ourselves - CHI '02, ACM Press. URL: https://doi.org/10.1145%2F503376.503414, doi:10.1145/503376.503414.

Field, A., Hole, G., 2002. How to design and report experiments. Sage.

Gardony, A.L., Brunyé, T.T., Mahoney, C.R., Taylor, H.A., 2013. How navigational aids impair spatial memory: Evidence for divided attention. Spatial Cognition & Computation 13, 319–350. URL: https://doi.org/10.1080%2F13875868.2013.792821, doi:10.1080/13875868.2013.792821.

Gee, J.P., 2005. Learning by Design: Good Video Games as Learning Machines. E-Learning 2, 5–16. URL: http://www.editlib.org/p/68984/, doi:10.2304/elea.2005.2.1.5.

Grindlay, G., 2008. Haptic guidance benefits musical motor learning. Symposium on Haptics Interfaces for Virtual Environment and Teleoperator Systems 2008 - Proceedings, Haptics , 397–404doi:10.1109/HAPTICS.2008.4479984.

Gutwin, C., Vicencio-Moreira, R., Mandryk, R.L., 2016. Does Helping Hurt?: Aiming Assistance and Skill Development in a First-Person Shooter Game, in: Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play, ACM. pp. 338–349. URL: http://doi.acm.org/10.1145/2967934.2968101, doi:10.1145/2967934.2968101.

Hardwick, D.A., McIntyre, C.W., Pick, H.L., 1976. The content and manipulation of cognitive maps in children and adults. Monographs of the Society for Research in Child Development 41, 1. URL: https://doi.org/10.2307%2F1165952, doi:10.2307/1165952.

Hart, S.G., Staveland, L.E., 1988. Development of NASA-TLX (task load index): Results of empirical and theoretical research, in: Advances in Psychology. Elsevier, pp. 139–183. URL: https://doi.org/10.1016%2Fs0166-4115%2808%2962386-9, doi:10.1016/s0166-4115(08)62386-9.

Hasher, L., Zacks, R.T., 1979. Automatic and effortful processes in memory. Journal of Experimental Psychology: General 108, 356–388. URL: https://doi.org/10.1037%2F0096-3445.108.3.356, doi:10.1037/0096-3445.108.3.356.

Heinen, T., Pizzera, A., Cottyn, J., 2009. When is manual guidance effective for the acquisition of complex skills in Gymnastics? International Journal of Sport Psychology 40, 1–22.

Holding, D.H., Macrae, A.W., 1964. Guidance, Restriction and Knowledge of Results. Ergonomics 7, 289–295. URL: http://www.tandfonline.com/doi/abs/10.1080/00140136408930748, doi:10.1080/00140136408930748.

Honeybourne, J., Hill, M., Moors, H., 2000. AS Level Textbook. Nelson Thornes Limited.

Howard, J.T., 2003. Physical Guidance in Motor Learning. Ph.D. thesis. Queensland University of Technology.

Hund, A.M., Minarik, J.L., 2006. Getting from here to there: Spatial anxiety, wayfinding strategies, direction type, and wayfinding efficiency. Spatial Cognition &amp Computation 6, 179–201. URL: https://doi.org/10.1207%2Fs15427633scc0603_1, doi:10.1207/s15427633scc0603_1.

id Software, 2018. GtkRadiant. URL: http://icculus.org/gtkradiant/.

Ishikawa, T., Fujiwara, H., Imai, O., Okabe, A., 2008. Wayfinding with a GPS-based mobile navigation system: A comparison with maps and direct experience. Journal of Environmental Psychology 28, 74–82. URL: https://doi.org/10.1016%2Fj.jenvp.2007.09.002, doi:10.1016/j.jenvp.2007.09.002.

Johanson, C., 2020. colbyj/bride-of-frankensystem 1.1. URL: https://doi.org/10.5281/zenodo.3738761, doi:10.5281/zenodo.3738761.

Johanson, C., Gutwin, C., Mandryk, R.L., 2017. The effects of navigation assistance on spatial learning and performance in a 3d game, in: Proceedings of the Annual Symposium on Computer-Human Interaction in Play, pp. 341–353.

Johanson, C., Mandryk, R.L., 2016. Scaffolding Player Location Awareness through Audio Cues in First-Person Shooters, in: Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM. pp. 3450–3461. URL: http://doi.acm.org/10.1145/2858036.2858172, doi:10.1145/2858036.2858172.

Johnson, A., 2004. We Learn from our Mistakes – Don't We? Ergonomics in Design: The Quarterly of Human Factors Applications 12, 24–27. URL: http://erg.sagepub.com/lookup/doi/10.1177/106480460401200206, doi:10.1177/106480460401200206.

Jul, S., Furnas, G.W., 1997. Navigation in electronic worlds. ACM SIGCHI Bulletin 29, 44–49. URL: https://doi.org/10.1145%2F270950.270979, doi:10.1145/270950.270979.

Juul, J., 2013. The art of failure: An essay on the pain of playing video games. Mit Press.

Khan, N., Rahman, A.U., 2017. Rethinking the mini-map: A navigational aid to support spatial learning in urban game environments. International Journal of Human–Computer Interaction 34, 1135–1147. URL: https://doi.org/10.1080%2F10447318.2017.1418804, doi:10.1080/10447318.2017.1418804.

Kolb, D.A., 1984. Experiential Learning: Experience as the Source of Learning and Development. Prentice Hall, Englewood Cliffs, NJ. URL: https://books.google.se/books?id=jpbeBQAAQBAJ&pg=PR4&dq=10:0-13-389240-9&hl=en&sa=X&ved=0ahUKEwjH2sTY9vPRAhXBHJoKHYuUDIQQuwUIHTAA#v=onepage&q=10%3A0-13-389240-9&f=false.

Lawton, C.A., Kallai, J., 2002. Gender differences in wayfinding strategies and anxiety about wayfinding: A cross-cultural comparison. Sex roles 47, 389–401.

Leshed, G., Velden, T., Rieger, O., Kot, B., Sengers, P., 2008. In-car gps navigation: Engagement with and disengagement from the environment, in: Proceeding of the twenty-sixth annual CHI conference on Human factors in computing systems - CHI '08, ACM Press. URL: https://doi.org/10.1145%2F1357054.1357316, doi:10.1145/1357054.1357316.

Lin, J., Cao, L., Li, N., 2019. Assessing the influence of repeated exposures and mental stress on human wayfinding performance in indoor environments using virtual reality technology. Advanced Engineering Informatics 39, 53–61. URL: https://www.sciencedirect.com/science/article/pii/S1474034618304014, doi:https://doi.org/10.1016/j.aei.2018.11.007.

Lionhead Studios, 2008. Fable II. Microsoft Game Studios. Game [Xbox 360].

MacKenzie, I.S., 2012. Human-computer interaction: An empirical research perspective .

Macrae, A.W., Holding, D.H., 1966. Transfer of training after guidance or practice. Quarterly Journal of Experimental Psychology 18, 327–333. URL: http://www.tandfonline.com/doi/abs/10.1080/14640746608400050, doi:10.1080/14640746608400050.

Magill, R., 2007. Motor Learning and Control: Concepts and Applications. McGraw-Hill International Edition, McGraw-Hill. URL: https://books.google.ca/books?id=rCPdAAAACAAJ.

Marples, D., 2017. The Influence of Intrinsic Perceptual Cues on Navigation and Route Selection in Virtual Environments. Ph.D. thesis. University of Huddersfield.

Maxwell, J., Masters, R., Kerr, E., Weedon, E., 2001. The implicit benefit of learning without errors. The Quarterly Journal of Experimental Psychology A 54, 1049–1068. URL: http://www.catchword.com/cgi-bin/cgi?body=linker&ini=xref&reqdoi=10.1080/02724980143000073, doi:10.1080/02724980143000073.

McAuley, E., Duncan, T., Tammen, V.V., 1989. Psychometric properties of the intrinsic motivation inventory in a competitive sport setting: A confirmatory factor analysis. Research Quarterly for Exercise and Sport 60, 48–58. URL: https://doi.org/10.1080%2F02701367.1989.10607413, doi:10.1080/02701367.1989.10607413.

McCullagh, P., Meyer, K.N., 1997. Learning versus correct models: Influence of model type on the learning of a free-weight squat lift. Research Quarterly for Exercise and Sport 68, 56–61.

Montello, D.R., 2005. Navigation, in: The Cambridge Handbook of Visuospatial Thinking. Cambridge University Press, pp. 257–294. URL: https://doi.org/10.1017%2Fcbo9780511610448.008, doi:10.1017/cbo9780511610448.008.

Moura, D., El-Nasr, M.S., 2014. Design techniques for planning navigational systems in 3-d video games. Computers in Entertainment 12, 1–25. URL: https://doi.org/10.1145%2F2701657.2633421, doi:10.1145/2701657.2633421.

Münzer, S., Zimmer, H.D., Baus, J., 2012. Navigation assistance: A trade-off between wayfinding support and configural learning support. Journal of Experimental Psychology: Applied 18, 18–37. URL: https://doi.org/10.1037%2Fa0026553, doi:10.1037/a0026553.

Nazca Corporation, 1996. Metal Slug. SNK. Game [Arcade].

Newell, K.M., 1981. Skill Learning, in: Human Skills, pp. 203–226.

Pollock, B.J., Lee, T.D., 1992. Effects of the model's skill level on observational motor learning. Research quarterly for exercise and sport 63, 25–29.

Prather, D.C., 1971. Trial-and-error versus errorless learning: Training, transfer, and stress. The American journal of psychology , 377–386.

Rohbanfard, H., Proteau, L., 2011. Learning through observation: a combination of expert and novice models favors learning. Experimental Brain Research 215, 183–197.

Ruddle, R.A., 2001. Navigation: Am i really lost or virtually there? Engineering psychology and cognitive ergonomics 6, 135–142.

Schmidt, R.A., Lee, T.D., Winstein, C.J., Wulf, G., Zelaznik, H.N., 2018. Motor Control and Learning, 6E. Langara College.

Schmidt, R.A., Young, D.E., Swinnen, S., Shapiro, D.C., 1989. Summary knowledge of results for skill acquisition: support for the guidance hypothesis. Journal of Experimental Psychology: Learning, Memory, and Cognition 15, 352.

Schneider, B.A., Avivi-Reich, M., Mozuraitis, M., 2015. A cautionary note on the use of the analysis of covariance (ANCOVA) in classification designs with and without within-subject factors. Frontiers in Psychology 6. URL: https://doi.org/10.3389%2Ffpsyg.2015.00474, doi:10.3389/fpsyg.2015.00474.

Singer, R.N., 1980. Motor Learning and Human Performance: An Application to Motor Skills and Movement Behaviors. MacMillan. URL: https://books.google.ca/books?id=zD1kQgAACAAJ.

Singer, R.N., Gaines, L., 1975. Brief Note: Effects of Prompted and Problem-solving Approaches on Learning and Transfer of Motor Skills. American Educational Research Journal 12, 395–403.

Singer, R.N., Pease, D., 1976. A comparison of discovery learning and guided instructional strategies on motor skill learning, retention, and transfer. Research Quarterly. American Alliance for Health, Physical Education and Recreation 47, 788–796.

Singer, R.N., Pease, D., 1978. Effect of guided vs. discovery learning strategies on initial motor task learning, transfer, and retention. Research Quarterly. American Alliance for Health, Physical Education and Recreation 49, 206–217.

Smith, T.W., 1982. Olympic Decathlon. Microsoft Consumer Products. Game [PC].

Splash Damage, 2003. Wolfenstein: Enemy Territory. Activision. Game [PC].

Summers, J.J., 1989. Motor programs, in: Human Skills. John Wiley & Sons, pp. 49–70.

Taylor, H.A., Naylor, S.J., Chechile, N.A., 1999. Goal-specific influences on the representation of spatial perspective. Memory & Cognition 27, 309–319. URL: https://doi.org/10.3758%2Fbf03211414, doi:10.3758/bf03211414.

Thorndyke, P.W., Goldin, S.E., 1983. Spatial learning and reasoning skill, in: Spatial Orientation. Springer US, pp. 195–217. URL: https://doi.org/10.1007%2F978-1-4615-9325-6_9, doi:10.1007/978-1-4615-9325-6_9.

Thorndyke, P.W., Hayes-Roth, B., 1982. Differences in spatial knowledge acquired from maps and navigation. Cognitive Psychology 14, 560–589. URL: https://doi.org/10.1016%2F0010-0285%2882%2990019-6, doi:10.1016/0010-0285(82)90019-6.

Thorndyke, P.W., Stasz, C., 1980. Individual differences in procedures for knowledge acquisition from maps. Cognitive Psychology 12, 137–175. URL: https://doi.org/10.1016%2F0010-0285%2880%2990006-7, doi:10.1016/0010-0285(80)90006-7.

Tomporowski, P.D., 2003. The Psychology of Skill: A Life-span Approach. Praeger Publishers. URL: https://books.google.ca/books?id=QaN9AAAAMAAJ.

Turgut, M., 2014. Development of the spatial ability self-report scale (SASRS): reliability and validity studies. Quality & Quantity 49, 1997–2014. URL: https://doi.org/10.1007%2Fs11135-014-0086-8, doi:10.1007/s11135-014-0086-8.

u/CherrySlurpee, 2016. r/gaming - CMV: Quest markers are one of the worst things to ever happen to video games, and they're ruining the concept of immersion. reddit URL: https://www.reddit.com/r/changemyview/comments/4nnt79/cmv_quest_markers_are_one_of_the_worst_things_to/.

Unity Technologies, 2018. Unity. URL: http://unity.com.

Vicencio-Moreira, R., Mandryk, R.L., Gutwin, C., 2015. Now You Can Compete With Anyone: Balancing Players of Different Skill Levels in a First-Person Shooter Game, in: Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM, New York, NY, USA. pp. 2255–2264. URL: http://doi.acm.org/10.1145/2702123.2702242, doi:10.1145/2702123.2702242.

Vicencio-Moreira, R., Mandryk, R.L., Gutwin, C., Bateman, S., 2014. The Effectiveness (or Lack Thereof) of Aim-Assist Techniques in First-Person Shooter Games, in: CHI'14: Proceedings of the 2014 CHI international conference on Human factors in computing systems, Toronto, Canada. pp. 937–946.

Vygotsky, L., 1978. Interaction between learning and development. doi:10.1016/S0006-3495(96)79572-3.

Waller, D., Hunt, E., Knapp, D., 1998. The transfer of spatial knowledge in virtual environment training. Presence: Teleoperators and Virtual Environments 7, 129–143. URL: https://doi.org/10.1162%2F105474698565631, doi:10.1162/105474698565631.

Waters, R.H., 1930. The Influence of Large Amounts of Manual Guidance upon Human Maze Learning. The Journal of General Psychology 4, 213–228. URL: http://www.tandfonline.com/doi/abs/10.1080/00221309.1930.9918311, doi:10.1080/00221309.1930.9918311.

Wingfield, A., 1979. Human learning and memory: an introduction. Harper & Row. URL: https://books.google.ca/books?id=dEMQAQAAIAAJ.

Winstein, C.J., Pohl, P.S., Lewthwaite, R., 1994. Effects of Physical Guidance and Knowledge of Results on Motor Learning: Support for the Guidance Hypothesis. Research Quarterly for Exercise and Sport 65, 316–323. URL: http://www.tandfonline.com/doi/abs/10.1080/02701367.1994.10607635, doi:10.1080/02701367.1994.10607635.

Witmer, B.G., Singer, M.J., 1998. Measuring presence in virtual environments: A presence questionnaire. Presence: Teleoperators and Virtual Environments 7, 225–240. URL: https://doi.org/10.1162%2F105474698565686, doi:10.1162/105474698565686.

Wulf, G., Shea, C.H., 2002. Principles derived from the study of simple skills do not generalize to complex skill learning. Psychonomic bulletin & review 9, 185–211.

Wulf, G., Shea, C.H., Whitacre, C.A., 1998. Physical-Guidance Benefits in Learning a Complex Motor Skill. Journal of Motor Behavior 30, 367–380. URL: http://www.tandfonline.com/doi/abs/10.1080/00222899809601351, doi:10.1080/00222899809601351.

Zagata, K., Medyńska-Gulij, B., 2023. Mini-map design features as a navigation aid in the virtual geographical space based on video games. ISPRS International Journal of Geo-Information 12, 58. URL: https://doi.org/10.3390%2Fijgi12020058, doi:10.3390/ijgi12020058.