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Virtual Reality in Investigation of Human Navigational Skills

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Abstract. *In recent years, virtual reality has been successfully employed in numerous studies concerning human navigational skills. This mini-survey reviews several of them, presenting their methodology and main findings, as well as discusses advantages and disadvantages of various types of virtual reality systems that have been adopted. Moreover, it provides an overview of navigational behaviors and a brief characterization of the possible cognitive processes that underlie them.*
Keywords: *navigation, virtual reality.*

1. Introduction

Navigation is an important capability for any motile species, including humans. It allows animals to reach significant places in their environments, such as home, food sources, or shelter. Likewise, it enables humans to repeatedly travel to work, home, to shopping centers, or to places of leisure. However, what specific skills are involved in navigation and what computational processes in the nervous system underlie it is still not fully understood.

The advent and proliferation of virtual reality (VR) systems in recent years has made it possible to utilize this powerful technology in investigation of the navigational skills in humans as well as in studying the underlying processes. Indeed, VR offers extraordinary advantages, which are hard to gain otherwise. First, it allows precise control of various confounds during experiments, with respect both to the environment itself and to the sensory perception. For example, virtual environments can be engineered to expose or hide particular parts of the scene or specific sensory signals can be eliminated, such as vestibular cues during motion. Second, the environment may be subject to abrupt changes during the course of an experiment, which are not possible in the real world, for instance landmarks may swap locations or appearance, such as their shape or color, in an attempt to trick the navigational system. Third, it is possible to introduce teleportation and consequently create non-Euclidean environments.

This mini-survey reviews several important studies on human navigational skills in which VR was successfully adopted. It first gives an overview of navigational behaviors that have been identified in animals. Then, it briefly characterizes the possible cognitive processes that have been determined to facilitate these skills. Next, it describes adaptation of various types of VR systems to human navigation research and discusses their advantages and disadvantages. It subsequently presents findings from various experiments and finally provides some conclusions.

2. Navigational Behaviors

Navigation is defined as the process of determining and maintaining a course or trajectory from one place to another [11]. It can be generally divided into local navigation and way-finding [7, 11]. *Local navigation* involves only the currently available perceptions and a representation of the goal. In particular, objects and places outside the current range of perception (with the possible exception for the goal) are not internally represented. In contrast, *way-finding* additionally requires representations of objects and places other than the goal, possibly together with representations of relations among them, where some of these objects and places may be outside the current range of perception. Therefore, way-finding builds on top of local navigation, allowing one to reach goals that could not be reached by local navigation alone.

Four different behaviors have been identified to support local navigation [7]. The simplest one is *search* [7], which does not involve any active orientation towards the goal; instead, the goal is encountered only by chance when moving around. The second one is *direction-following* [7]. Here, active orientation is achieved based on locally available cues; importantly, the goal itself does not need to be directly perceivable. For example, direction to the goal may be derived from celestial cues, such as sun position. Moreover, the established direction can optionally be combined with information on the expected distance. This behavior, however, is very sensitive to misalignment or deviation from the course as in such circumstances the goal can easily be missed. The third behavior is *aiming*. It requires that the goal be directly perceivable, either visually or using some other cues, such as olfactory or auditory. As a result, it is possible to move towards the goal by monitoring how perceptions of the cues corresponding to the goal change during motion and responding appropriately. Usually, aiming can be performed from many locations around the goal and thus from many different directions. Finally, the fourth behavior is *guidance* [7, 11]. It can occur when the goal is not directly perceivable, but one or more landmarks in the vicinity of the goal are and the spatial relation of that landmark or the configuration of landmarks with respect to the goal is known. In these conditions, the goal can be approached by comparing the currently perceived configuration of landmarks with the memory of such configuration previously acquired at the goal and by moving such that the two would eventually match.

Way-finding, on the other hand, comprises three behaviors [7]. The first one is *recognition-triggered response* [7, 11]. It is based on an acquired association between a place other than the goal and a specific action, namely execution of particular motion that is supposed to be executed once the location is reached. For example, at some location turning left followed by proceeding forward may be necessary as otherwise the goal would be missed. In general, many such associations involving various places and corresponding actions can be learned; moreover, acquiring associations related to different goals is possible as well. Furthermore, if appropriate, these associations can also form sequences, thus giving rise to memories of routes. The second behavior is *topological navigation* [7, 11], which can arise once a specific spatial representation of the environment, called topological representation, emerges from route integration. This can happen if the environment contains many goals and routes to different goals intersect or even partially overlap. In such a case, common places can be identified, even if they are associated with different actions due to the different goals, which, in turn, can lead to integration of those routes into an overall representation of the environment that in mathematical terms corresponds to a graph, where nodes are places and edges are route segments. Importantly, in this representation distances between pairs of places are not preserved; it is only the connectivity that is internally maintained. Finally, the third behavior is *survey* (or *metric*) *navigation* [7, 11]. It can occur when the topological representation becomes embedded in a common reference frame that preserves metric distances, thus giving rise to an internal metric map. In contrast to topological navigation, in which novel routes can only be formed by concatenating parts of the remembered routes, survey navigation also allows developing new shortcuts over an unknown territory if such a territory is surrounded by known places.

3. Cognitive Processes

A number of cognitive processes are involved in navigation [4].

One of these processes is *path integration*, which is based on integrating all directions steered and distances covered from a specific place, usually a starting location. Such integration can be carried out using either internal or external cues, or both. As a result, an estimate of the current position in the environment with respect to that starting location is derived and internally maintained. This estimate is often not very accurate because path integration is highly sensitive to accumulation of errors.

Another cognitive process is *place recognition*. Places can be recognized either visually or using other modalities by comparing current perceptions with memories previously acquired at those places. This process is necessary for detecting arrival at the goal or at other significant places in the environment. Moreover, recognition of a particular place can contribute to determining the current position independently from path integration.

The next cognitive process involves *identifying decision points* and builds on top of place recognition. Decision points correspond to those places encountered during a journey where a decision needs to be made regarding what course should be followed next, for instance whether to proceed forward or turn left. Clearly, such decisions are not made everywhere and not every place that can be recognized becomes a decision point. Therefore, this process selects a subset of all recognized places and attributes additional navigational significance to them.

The next cognitive process, which in turn builds on top of identification of decision points, is *response learning*. In involves forming associations between decision points and corresponding actions and is essential for producing recognition-triggered responses.

When a route is traversed, decision points are encountered in a particular order, and their succession can be learned as a sequence. This is possible owing to another cognitive process, namely *sequence learning*. It is an important process because it introduces expectations to navigation: taking a particular action at a given decision point, determined by the recognition-triggered response, is now followed by an expectation regarding the next decision point to be reached. Consequently, this process enables easier detection of navigational errors: if the next decision point does not appear as expected, this indicates that some error must have been made on the way.

Finally, *place recognition within the larger environment* makes it possible not only to recognize a particular place, but also to localize it within a broader environmental context, for instance with respect to other places that are nearby. This process depends on topological or survey representations of the environment and is fundamental to more advanced skills such as path planning.

The cognitive processes described above can be considered high-level and as such, they critically depend on several processes that operate at a lower level [4].

One crucial low-level process, which underlies many of the high-level ones, is *forming associations*. Associations are formed between decision points and corresponding actions, giving rise to recognition-triggered responses, between preceding and succeeding decision points along a route, thus enabling sequence learning, or as a result of route integration, whereby common places on different routes are identified and matched; consequently, forming associations is also essential for developing a topological representation of the environment.

Another important low-level process is *transformation between allocentric and egocentric perspectives*. Egocentric perspective is the one that is directly perceived by the navigator, whereas allocentric perspective is based on a reference frame that uses external coordinates that are independent of the navigator. Such transformations enable, among other things, making correct decisions when approaching places from different directions. For example, if reaching a specific goal requires turning left at a particular place when approached from one direction, then when the same place is approached from the opposite direction it is a right turn that needs to be executed.

4. Adaptation of Virtual Reality Systems

Three types of VR systems have been adopted in various studies concerning human navigational skills: fully immersive VR systems, desktop VR systems, and VR systems coupled to fMRI (functional magnetic resonance imaging). They differ in the range of stimuli that they deliver and hence how realistic experience they can generate, in kinds of data that can be collected, as well as in other aspects, such as cost or difficulty to set up.

As regards stimuli that occur during navigation, they can be broadly divided into idiothetic and allothetic cues. *Idiothetic cues* comprise motion-related signals that are generated internally: they include motor commands send to muscles as well as cues produced by vestibular and priopriocetive organs, the latter of which are responsible for sensing the relative positions of individual body parts along with strength employed in movement. Sometimes motor commands together with proprioceptive information are called *podokinetic cues*. By contrast, *allothetic cues* refer to external cues such as landmarks.

Fully immersive VR systems require the subject to wear a special headset that includes one or two screens right in front of the eyes, in which an image of a virtual environment is displayed. Subjects can move their heads as well as walk, while the apparatus tracks their movements so that the view of the environment could be updated accordingly. Generating and updating the virtual environment is usually carried out by a powerful workstation. These systems offer much more realistic experience than any other type of VR systems because the subject can feel fully immersed in the virtual environment and both allothetic and idiothetic cues are present. On the other hand, these systems are rather expensive, require special equipment described above and often special rooms designated to conduct studies, which need to provide large enough space for free walking. Moreover, the equipment can be cumbersome if tethered, potentially demanding that the subject be followed by another person that takes care of the cables. Sometimes latency effects can also become conspicuous, that is a delay in updating the view can be noticed, and in some people using such systems can induce motion sickness. Notwithstanding their disadvantages, fully immersive VR systems offer excellent features, owing to which they have been adopted in numerous studies [5, 6, 12, 13].

By contrast, *desktop VR systems* display an image of a virtual environment on a stationary screen in front of a subject that sits at some distance from it. Sometimes instead of a single screen, an array of screens is used that together span a wider extent of a virtual panorama. The subject commands their moves in the virtual environment using a keyboard or another controller such as a joystick. These systems are much cheaper than their fully immersive counterparts as they require only a modern computer with a large display, occasionally with additional popular equipment such as a gamepad or joystick. Consequently, they are also much easier to set up, whereas studies in which they are utilized can be conducted in almost any room where a computer can be installed. The main disadvantage of these systems is the absence of idiothetic cues (although in some circumstances this may actually be advantageous). As a result, prioprioceptive and vestibular stimuli along with motor commands, which all reflect the subject posture and actions in the real world, remain in conflict with visual and auditory stimuli, which originate in the virtual environment. Usually in such circumstances vision tends to override conflicting information from other senses, but perception is definitely not as well integrated as in the case of fully immersive systems. Because of those perceptual inconsistencies, some results from studies using desktop VR were found to be inconclusive. Another disadvantage of these systems is that the subject is not separated from the real world, which can still be perceived. Nevertheless, desktop VR systems have also been widely used in numerous studies [1, 2, 8, 9, 10].

Finally, *VR systems coupled to fMRI* combine VR with simultaneous monitoring of the ongoing activity in the subject's brain. During examination, the subject lies horizontally in an fMRI scanner, a sophisticated device that collects data related to brain activity, while an image of a virtual environment is displayed on a screen mounted inside the scanner, close to the subject's eyes. Moves in the virtual environment are commanded by the subject by means of button presses using a special controller. Unlike other VR systems, these systems provide detailed information on activity in individual brain regions during a navigational task. Importantly, this is achieved relatively safely because fMRI is a non-invasive technique, which does not require implantation of electrodes inside the head. However, these systems are extremely expensive due to the very high cost of an fMRI scanner. They also require special rooms as well as trained personnel to carry out examination. Similarly to desktop VR systems, they lack idiothetic cues. Moreover, the subject's horizontal position in the scanner is far from the one that is naturally assumed for movement, which puts vestibular cues in substantial conflict with other stimuli. Furthermore, because subjects are enclosed in the narrow tube inside the scanner, people suffering from claustrophobia cannot participate in such studies. Despite their deficiencies, these systems offer excellent means for observing large-scale brain activity during navigational tasks, which consequently enables inference of the functions of particular brain structures, ultimately leading to important findings, such as those reported in [3].

5. Important Findings

VR systems have been adopted in numerous studies concerning human navigational skills. This section reviews only a small sample of them, focusing on such problems as use of navigational cues, learning routes and environments, brain structures that support navigation, and navigational deficits related to diseases.

5.1. Use of Navigational Cues

One question addressed in research of human navigational skills is what environmental cues are used during navigation; it is closely related to another important question, namely how different cues are combined.

These two questions were addressed in one study by Mallot and Gillner [10], in which a desktop VR system was employed. The virtual environment was a small town called Hexatown, which comprised several streets whose intersections always resembled the letter “Y" (giving rise to the hexagonal layout of streets and consequently the name of the town). On each of the three sides of every intersection, there was a unique building. Participants were first trained to learn a route from a starting location to the goal, which required making correct turn decisions at a few intersections on the way. Then, they were released at some point along the route and were asked to continue to the goal. However, this time buildings located at intersections had been swapped: in some cases they had been swapped within an intersection (i.e., they remained at the same intersection as before, but were on different sides) and in other cases they were swapped between intersections, either in a consistent manner (all buildings at an intersection after the swap were associated with the same turn decision) or in an inconsistent manner (different buildings at an intersection were associated with different turn decisions). It was found that if all buildings that ended up at a particular intersection had been associated with the same turn decision, subjects made the respective decision easily. However, if buildings at an intersection had been associated with different turn decisions, subjects’ responses were impaired. The authors conclude that subjects did not recognize places as configuration of landmarks, but rather landmarks were recognized individually, and the individually associated turn decisions contributed to the final response in a voting scheme.

In another study, in which a fully immersive VR system was employed, Zhao and Warren [13] investigated interaction between path integration and landmark guidance, namely whether their cues are integrated or they rather compete. The virtual environment was mostly an empty scene with only a few landmarks, in which participants were trained to walk on an unmarked path in the shape of a triangle and then continue to the goal. In some trials, unknown to the subjects, the landmarks were shifted after following the shape of the triangle was completed. It was found that when the subjects continued to the goal, their choice of direction was dominated by a single cue: these directions were dictated solely by landmarks provided that the landmarks were shifted up to 90 degrees, and solely by path integration if the landmarks were shifted more than 90 degrees. Therefore, cues were used in a competitive manner to determine direction. However, when variability of directions was examined, it was found that, as long as the landmarks were shifted up to 90 degrees, landmark and path integration cues were combined, which allowed reduction in response variability to a greater degree. The authors ultimately conclude that cue integration and cue competition govern different aspects of navigational responses.

The goal of another study, conducted by Chrastil and Warren [5] using a fully immersive VR system, was to determine what information contributes to development of internal metric maps. Participants first explored a virtual hedge maze, in which eight places were distinguished by means of unique objects located there. Subjects in one group could walk, those in another group were pushed in a wheelchair, whereas those in yet another group could only watch a video. Each group was divided into two subgroups: in the first one participants made decisions about their path on their own and in the other one they were guided through the maze. Having familiarized with the maze, participants were asked to demonstrate their survey knowledge by walking a novel shortcut with the maze removed. It was found that participants that only watched a video or were pushed in a wheelchair performed worse than those that could walk, whereas making decisions on one's own versus being guided did not have any effect. The authors conclude that survey knowledge is primarily derived from podokinetic cues.

In a subsequent study by the same authors [6], in which the same environment was used, a complementary question was addressed: what information contributes to development of topological knowledge? There were two groups of participants: those in the first group could walk, whereas those in the other group could only watch a video. As before, each group was divided into two subgroups depending on whether participants made decisions about their path on their own or they were guided through the maze. Having familiarized with the maze, subjects were asked to demonstrate their topological knowledge by navigating from a starting location to the given goal. In some trials, obstacles emerged on the way, thus forcing participants to devise detour paths. It was found that subjects that made decisions about their path on their own performed better than those who were guided; this was true, however, only if idiothetic cues were available. The authors conclude that decision making is the main contributor to development of topological knowledge.

5.2. Learning Routes and Environments

Another important problem regarding human navigational skills is how people acquire spatial information about their environments. One of its aspects specifically concerns learning routes.

These questions were addressed in an early study by Aginsky et al. [1], in which a desktop VR system was employed. The virtual environment was a town with a number of roads and their intersections as well as various buildings. Participants were supposed to learn a specific route in that town by driving a virtual car. Once learning was completed, they were asked to draw sketch maps depicting that route. These maps clearly revealed that although all subjects could follow the route correctly, their memories related to that route were substantially different. Some participants drew only a few isolated places, some others drew places that were connected in the right sequence, but distances and angles between places were incorrect, and yet others drew places connected in the right sequence with distances appearing much more accurate. In one of the tests, subjects were asked to drive along the route once again, but this time some buildings were changed: either their color, shape, or the side of the street at which they were located was different. It was found that not all changes were equally noticed; specifically, these at decision points where making a turn was necessary were detected much more readily than those at other places. The authors reached two conclusions. The first one is that people adopt different strategies to learning a route, which give rise to different representations: one group of people employs a visually dominated strategy, which involves visual recognition of decision points and recognition-triggered responses with no survey representation of the environment, whereas the other group utilizes a spatially dominated strategy, in which a survey representation is developed right from the beginning. This implies that, at least in some people, acquiring survey knowledge can occur simultaneously with learning landmarks and routes rather than as a subsequent stage following landmark and route learning.

The other conclusion is that people selectively learn details about spatial aspects of their environments: information related to the vicinity of decision points is more readily remembered than information concerning other places.

The above study dealt with learning a route in a virtual town, which is rather a structured environment. On the other hand, learning a route in an unstructured environment was addressed by Hurlebaus et al. [9]. In this study, which used a desktop VR system, the virtual environment was an open area cluttered with prismatic objects of equal height and texture. There were also four distal landmarks, namely large columns, each of a different color and located on a different side of the environment, far from the center. Participants were supposed to first explore the environment, find two locations marked by special spheres, which were termed “home" and the “feeder", respectively, and then shuttle between these two locations repeatedly. It was found that once participants learned both locations, they exhibited two different patterns of navigation: one group of subjects followed paths that were very consistent across trials, whereas the other group produced paths that were much more variable. Subsequently, participants were tested in two conditions. In the first one, subjects started at home and were asked to navigate to the feeder; once they arrived there, they were asked to return home, but this time all prismatic objects were removed and only the distal landmarks were visible. Participants that originally produced more variable paths were found to move along more or less straight lines when homing, while those that originally produced more consistent paths tended to move along rather curved lines, to some extent resembling their habitual routes. In the other condition, subjects were asked to shuttle between home and the feeder, but this time their view was obscured by fog, which made it impossible to see the distal landmarks as well as “corridors" arising from constellations of prismatic objects. It was found that in such situation participants originally producing variable paths performed worse than those producing consistent paths. The authors explain their findings by arguing that subjects in the group exhibiting more variable paths mostly relied on distal landmarks, whereas those in the group exhibiting more consistent paths rather exploited proximal cues. Consequently, they conclude that people vary depending on which of these two aspects of spatial information they utilize during navigation.

Learning routes along with the spatial structure of the environment was addressed in a study by Gillner and Mallot [8], in which a desktop VR system and the same Hexatown virtual environment as in [10] were employed. Participants first explored the environment by searching for places with particular views that were presented to them, in this way familiarizing themselves with a number of routes linking various places. As the exploration continued, they were monitored for changes in error rates and for possible transfer of knowledge among different routes. Moreover, the effect of different viewing conditions was taken into account: some subjects explored the environment at night while others explored it during daylight; furthermore, those that explored it during daylight, when approaching an intersection, could either see all the buildings at that intersection from a distance or were unable to see the buildings on the sides because those buildings were occluded by bushes or trees. The authors report several interesting findings. First, learning a route in one direction was not of much help when traversing the same route in the other direction. According to the authors, this may be due to the fact that returning resulted in encountering views from an entirely different perspective and hence interpreting such views as completely novel. Second, distance estimates between places correlated more with walking distances (i.e., along piecewise linear lines that actually linked places) rather than with Euclidean distances (i.e., direct straight lines) or “decision distances" (i.e., numbers of decision points on the linking routes). Third, when participants were asked to draw sketch maps of the environment, those produced by good navigators (as assessed by recorded error rates) contained more details and involved distances and angles between places that were more accurate. Importantly, it was found that in general maps were locally correct but globally inconsistent, that is places tended to be connected correctly, but angles and lengths of the connections were usually highly inaccurate. The authors finally conclude that topological knowledge about the environment can be acquired even though idiothetic cues are absent, which is consistent with findings reported in [6].

The form of spatial representation of the environment was also investigated by Warren et al. [12], who used a fully immersive VR system and a virtual hedge maze similar to that employed in [5, 6]. However, this time the maze contained what was called “wormholes", which, when entered, instantly teleported the participant to another location. Two of such wormholes were embedded in the maze, each bi-directionally linking a pair of distant places with each other. Remarkably, participants going through a wormhole were unaware of the teleportation because the locations at both ends of the wormhole looked alike as each was located in the middle of an identical corridor. While subjects were walking in the maze between various places, they eagerly used paths through wormholes since they gave rise to shorter routes. This, however, led to emergence of a non-Euclidean environment, but, surprisingly, participants did not notice the resulting geometrical inconsistencies. When they were later asked to draw sketch maps, they somehow unconsciously resolved the inconsistencies and produced maps that were Euclidean, although individual places on the maps were found not to be at their correct locations. The authors conclude that navigational knowledge about the environment in humans is represented neither in the form of a metric map nor a topological graph, but rather as a labeled graph, in which nodes correspond to places, whereas edges refer to connections between those places and are weighted by their respective metric distances. Importantly, however, these metric distances as well as angles between edges are only approximate and globally inconsistent, which also matches findings reported in [8] and stands in contrast to metric maps, where a topological representation is embedded in a common reference frame that preserves metric distances globally.

5.3. Brain Structures Supporting Navigation

How the brain handles navigation is an extremely important question in neuroscience. Consequently, numerous studies have been devoted to this problem.

One of them is a study conducted by Brown et al. [3], in which a VR system coupled to fMRI was employed. The specific question whose answer was sought asked which structures in the brain are particularly involved in mediating navigation along routes with overlapping segments. Participants were trained to navigate several different mazes, some of which shared common hallways in the middle of the correct path. It was found that the posterior hippocampus and the parahippocampal cortex exhibited greater bilateral activity when the subject was about to begin negotiating a maze whose middle hallway was shared with another maze than when a maze without any shared hallways was supposed to be negotiated. Moreover, entering the shared hallway elicited greater activity in the right posterior hippocampus and in the right parahippocampal cortex as well as greater bilateral activity in the orbitofrontal cortex. The authors conclude that brain regions typically associated with spatial and episodic memory, namely hippocampus, parahippocampal cortex, and orbitofrontal cortex, are those that are critical in mediating navigation along routes with overlapping segments.

5.4. Navigational Deficits in Diseases

VR systems can also be employed in investigation of navigational deficits in various diseases.

In one such study, Broadbent et al. [2] used a desktop VR to assess deficits during learning routes in people with Williams syndrome. Williams syndrome is a genetic disorder whose symptoms include a variety of visuospatial impairments. The virtual environment was a maze that in one condition was surrounded by distal landmarks located at specific places around it, whereas in the other condition no landmarks were present. Consequently, participants were divided into two groups. The first group learned the route through the maze when the landmarks were visible. It turned out that subjects with Williams syndrome were able to learn the route, but it took them longer than typically developing individuals who comprised a control group. After learning was complete, subjects were asked to negotiate the maze once again, but this time all landmarks were removed. It was found that in this situation the performance of subjects with Williams syndrome was much worse than that of typically developing individuals. The other group of participants, assigned to the condition in which landmarks were not available from the beginning, was also supposed to learn the route through the maze, but without relying on landmarks at all. To successfully complete this task, the correct sequential order of turns needs to be remembered. As it turned out, this condition proved too difficult for participants with Williams syndrome as they were unable to learn the route. Although typically developing individuals also found this condition harder, they made much fewer errors. The authors conclude that, compared with typically developing individuals, people with Williams syndrome rely much more on landmarks during navigation and seem not to be able to remember a sequential order of turns.

6. Conclusions

As this paper shows, adoption of VR to investigation of human navigational skills has led to a number of important insights, which would not be possible without the high-degree of controllability that it offers or without such unique features as introducing on-the-fly modifications or even non-Euclidean distortions to the environment.

Continuous improvement of VR systems in the future resulting in more realistic experience, fewer technological constraints, for instance owing to more common use of wireless rather than wired headsets, as well as in cost reduction may facilitate further research and bring about novel important findings.

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