

The influence of navigation interaction technique on perception and behaviour in mobile virtual reality

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ABSTRACT

In recent years the development of affordable virtual reality has opened up enormous possibilities for virtual rehabilitation, and the introduction of ultra-low cost mobile VR such as Google Cardboard has real potential to put virtual rehabilitation right into patient's homes. However, the limited interaction possibilities when a mobile phone is mounted into a headset mean that these devices are generally used for little more than passive viewing. In this paper we present an evaluation of three approaches to supporting navigation in mobile VR, and discuss some of the potential hazards and limitations.

1. INTRODUCTION

Until recently, Virtual Reality (VR) has been primarily the domain of experts in specialist laboratories. Whilst it has demonstrated great potential for rehabilitation, the high cost of the technology (Amer & Peralez, 2014) and technical knowledge required (Glegg et al., 2013) has created a barrier to uptake in many areas. However, in recent years there has been a paradigm shift in the accessibility of VR, with plummeting costs and increasing ease of use driving significant uptake at the consumer level. This opens up unprecedented opportunities for virtual rehabilitation, with the ability to deploy applications not only for use within clinical settings, but also directly into the homes of the patients.

This increased accessibility of VR inevitably presents new challenges for rehabilitation professionals, and in particular for those designing virtual rehabilitation applications. It is well established that interacting with VR can alter behaviour, and indeed, this is the very reason that VR has such potential for rehabilitation. However, it has previously been observed that increased availability of commercial off-the-shelf (COTS) games which involve physical interaction have led to an increase in physical injury amongst users (e.g., Bonis 2007), and it has also been demonstrated that there are a wide range of components within VR which may have an (unanticipated) effect on behaviour (Powell & Stevens, 2013). The rapid proliferation of consumer VR, without a clear understanding of how users will interact with these systems, may not only increase the risk of injury and adverse effects, but also deter future uptake of high quality virtual rehabilitation applications. Indeed, even leading consumer VR hardware suppliers recommend careful design in order to avoid unwanted side effects (Yao et al., 2014). This will become increasingly important as mobile phone technology improves, and in particular the processing and display of mobile graphics, leading to the emergence of this platform as a base for low cost virtual reality experiences (Steed & Julier, 2013).

2. BACKGROUND

The introduction in 2014 of the "Google Cardboard" virtual reality headset costing just a few dollars (Google, 2014), initiated a rapid proliferation of consumer VR applications, with over 1000 applications and 5 million users by January 2016 (Google, 2016). However, once the phone is mounted in the VR headset, the buttons and screen are generally no longer accessible to provide input to the applications, and control options are very limited. At the present time, they are used primarily for viewing 360 degree photos and videos, or for "passive entertainment" e.g. riding a virtual rollercoaster. The built-in accelerometers or gyroscopes included in most modern mobile phones offer a simple solution to basic tracking of head movement, allowing the user to look around in the virtual space. Active selection of objects can be achieved using head-orientation as a proxy for gaze direction, with extended fixation on an object triggering interaction (Sibert & Jacob, 2000). However, although active exploration is often not an option in mobile VR, the ability to navigate in a virtual environment should be one of the core tasks (Doug

A. Bowman, Kruijff, LaViola, & Poupyrev, 2004), and for many cognitive and physical rehabilitation applications, the ability to navigate within the virtual space is essential.

Bowman (Doug A. Bowman et al., 2004) divides navigation tasks into the components of 'way-finding' and 'travel', and it is this latter component which presents particular challenges for mobile VR. At its core, travel involves the movement of the viewpoint within the virtual environment from one place to another. This movement can be instantaneous or it can involve both temporal and spatial components. The most natural way to travel in VR is to track the actual movements of the body. However, full body motion tracking is challenging (Slater, 2014), and this limits the possibilities for control of travel in low-cost mobile VR platforms.

Designing effective techniques for travel is not a problem unique to VR, and indeed there is a substantial body of Human Computer Interaction (HCI) research exploring navigation in 2D and 3D interfaces. However, the way in which VR is experienced is quite different to traditional interfaces, and we cannot assume that design guidelines from traditional HCI can be applied in the same way to VR (Jacob et al., 2008). VR interaction research is still in fairly early stages, and there is a lack of authoritative guidance regarding many aspects of design (Yao et al., 2014). Furthermore, different user populations may well have different interaction priorities, particularly where there is already cognitive or motor deficit. Designing VR applications based purely on intuition is driven by highly individual assumptions, and in order to select the most appropriate interaction technique for a specific population, it is important to first understand how it may impact cognitive load and behaviour.

Although in many ways the VR experience is very different from desktop 3D interaction, many of the underlying principles of virtual travel remain the same. An effective travel technique should promote appropriate velocity, spatial awareness, ease of learning, ease of use, a sense of presence in the environment, and the ability to gather information about the environment during travel (D. A. Bowman, Koller, & Hodges, 1997). Which of these elements are most important will depend on both the type of user and the nature of the task, and it could be argued that for physical rehabilitation, the motor response of the user to the interaction is also of key importance.

2.1 Travel techniques

In order to create a framework for evaluation of travel techniques in 3D environments, Bowman established a taxonomy to break the techniques into their core components, which he defines as "Direction selection" (specifying direction of travel), "Conditions of input" (requirements for starting or stopping travel), and "Velocity selection" (the ability to accelerate or change / reverse speed) (D. A. Bowman, Koller, & Hodges, 1997). In order to provide these components, it is necessary to mediate interaction between the user and the mobile application. For headset-mounted mobile phones such as Google Cardboard, there are three levels of possible interaction.

2.1.1 Phone-mediated interaction. Most mobile phones already have a number of in-built sensors, and it is possible to leverage these to allow some level of interaction. Accelerometers or gyroscopes are available on most Smartphones, and these can be used to detect movement of the phone, particularly changes in orientation. For mobile VR, head tracking generally relies on motion detected by these sensors, updating tilt and turn, although unable to detect translational movement (Sharma, 2015). In practice, this means that rotations of the head can be linked to the viewpoint of the virtual camera, allowing 360 degree viewing from a fixed point, but not directly supporting any movement through the environment. Whilst this is acceptable for experiencing fixed-viewpoint content such as 360° photographs, it is not sufficient for exploration of a virtual environment. A common workaround seen in many applications is to use continuous motion, which is either constrained to a defined path (e.g. a rollercoaster or train ride), or allows free exploration within the bounds of a virtual environment, with travel being limited only by approaching fixed objects, such as walls, within the scene. With the latter technique, head orientation can be used to set the direction, with continuous motion which is effectively in the direction of gaze. This relates to 'Direction selection' in Bowman's taxonomy, and this is the approach selected for the first of our three experimental conditions.

2.1.2 Headset-mediated interaction. Most of the ultra-low-cost VR headsets such as Google Cardboard have a sliding magnet affixed to the side of the headset. Movement of this magnet can be detected by the phone's built-in magnetometer, allowing it to work as a proxy for a switch or button (Smus & Riederer, 2015). To date, applications using this magnet have focussed on its use for selection (e.g. choosing menu items), but it also has the potential to act as a "toggle" for initiating movement. This relates to the 'Conditions of input' in Bowman's taxonomy. Our second experimental condition combines this movement toggle switch technique with the direction selection approach described in 2.1.1

2.1.2 Externally-mediated interaction. The primary appeal of mobile VR is its low-cost and portability. It has no need of any external equipment in order to provide at least an entry level VR experience. However, in order to widen the options for interaction, it may be necessary to add some additional input hardware. As far as possible, this should also meet the criteria of low-cost, portability and ease of use. A number of low-cost headsets come supplied with a small Bluetooth controller, offering the potential for direct control of motion via the mini joystick,

and, as the input is analogue rather than digital, it can add an element of velocity control (albeit small due to the small range of input values which can be generated). This relates to the 'Velocity Selection' category in Bowman's taxonomy. For our third experimental condition we used the mini-joystick of the controller to directly control forward and backward motion, whilst retaining head orientation for selection of motion direction. It should be noted that we initially included the ability to strafe (left and right step) in the Bluetooth controls, but preliminary usability testing found that this seemed to trigger a strong feeling of disorientation and nausea. Furthermore, it is generally recommended to minimise the need for strafing within VR design (Yao et al., 2014), and so it was removed for this study.

2.2 Evaluating navigation techniques

Navigation is comprised of 'wayfinding', which is the cognitive process of determining a path, and 'travel', which is the control of the user's viewpoint motion within a Virtual Environment (D. A. Bowman et al., 1997). Navigation is not directly dependent on the specific interaction techniques, and thus is not the focus of this current study. Furthermore, the wayfinding component of a navigation task depends on a cognitive process which makes sense of visual cues and other aids within the virtual environment. It requires the acquisition of spatial knowledge, and this causes difficulties for some 20-30% of users (Sousa Santos et al., 2008), and can thus confound the results of an evaluation of travel techniques. Therefore, as far as possible, this confounder has been removed from the study by providing an opportunity to rehearse the navigation task, and by the use of verbal prompts to guide the users between target locations (section 3.3).

Travel is generally not an end in itself, but is necessary in order to move the user to important points within the environment. Moving within a virtual world involves both simple and complex manoeuvres, and both should be incorporated into any task designed to evaluate a navigation interface (Griffiths, Sharples, & Wilson, 2006). Simple manoeuvres should include cornering, 180° rotation, forward movement on a straight line, and reversal of direction. Complex manoeuvres include moving around objects or through doorways, and moving towards a specific target location. All of these manoeuvres were combined into a structured navigation task.

3. METHODOLOGY

The three techniques to be evaluated were based on Bowman's taxonomy of travel techniques (Section 2.1), with increasing levels of control of the movement (Table 1). Although some authors recommend separating the viewing direction from the travel direction (Doug A. Bowman, McMahan, & Ragan, 2012), this necessitates an additional input in order to set a travel direction which is independent of the viewpoint orientation. As the goal of this study is to evaluate techniques using restricted input choices, we implemented travel in the direction of head orientation for all three of the travel techniques.

Table 1. *The three travel techniques evaluated in the study (counterbalanced order)*

Condition	Level of control (Mapping to Bowman's travel taxonomy)
Continuous motion	Can only control the direction ('Direction selection')
Magnetic switch	Travel can be stopped and started using toggle switch ('Input condition')
Bluetooth controller	Direct control of forward and backward travel ('Velocity selection')

The nature of the study requires a within-subjects repeated measures design. This inevitably introduces two factors which may contribute to an order effect. Firstly, increasing familiarity with the virtual environment may improve task performance and user preferences. The introduction of a rehearsal phase will reduce but not eliminate this effect. Secondly, any travel technique will be evaluated in the context of any previous technique, and with the continuous motion and switch techniques there may also be a learning effect of the travel technique itself. In order to minimise the impact of these order effects on the results, the study was designed as a counterbalanced study, with 6 different sequences of test order. Participants were sequentially assigned to the sequences in 3 blocks of 6.

In order to achieve a repeatable task which incorporated the required simple and complex tasks, a route was designed around a virtual flat, visiting six locations in sequence (Figure 1). The travel task involved forward motion, several 90° and 180° turns, reversing direction, manoeuvring around objects, passing in and out of two doorways, and planning routes to move towards target objects.



Figure 1. The six target locations visited in the study in sequence from left to right, before returning to the starting location.

3.1 Participants

Low-cost VR is designed to appeal to a wide range of the population, and so there was no specific target user group for this evaluation. Eighteen (18) participants were recruited from academic, support and administrative staff at the University of Portsmouth. There were 12 male and 6 female participants, ranging in age from 22-60 years old, with a mean age of 44, with a mix of background experience from VR enthusiasts to those who had never experienced VR before. Most of the participants were healthy adults, but one had moderate Parkinson's Disease (PD). Each volunteer was given a short introduction to the study and the three techniques to be evaluated, before giving their informed consent to proceed.

3.2 Equipment

A virtual flat was built in Autodesk 3D studio max and deployed in the Unity game engine, using the Google Cardboard virtual camera as the viewer. Models and textures were optimised for rendering on an Android phone, running at approximately 30 frames per second (fps). For each technique, the movement was set at the same (steady walking) speed of 1.5m/s. For the Bluetooth controller there was some scope for setting a lower velocity using the analogue joystick. In practice, the small size of the joystick and very small range of motion (+/- 2mm) meant that for all practical purposes it was always used at its maximum input value, equivalent to 1.5m/s.

The application was deployed as an .apk file onto a Nexus 6 mobile phone, which was mounted inside a DeFairy VR headset. The controller used was a DeFairy mini Bluetooth controller, mapped to allow only forward and backward movement using the mini joystick. Participants were seated throughout the tasks on a swivel chair with armrests (Figure 2).



Figure 2. The experimental setup

An operator view was mirrored in real-time on a standard PC laptop computer, and this was connected via a local wireless network to the mobile phone. This enabled the observer to track the progress of the participant throughout the task, and provide consistent and timely verbal prompts for each target location.

3.3 Procedure

Participants were briefed on the task and the techniques. They were then given an opportunity to rehearse the task and to familiarise themselves with the virtual environment, using keyboard controls and a laptop computer. Following the rehearsal, they completed the navigation task sequence using the VR headset three times, once for each travel technique, and answered a short series of questions after each trial. As the study did not involve memory or cognition testing, each time the participants reached a target location they were given a verbal prompt to direct them to the next location.

Each trial was timed from the start of movement until returning to the hallway at the end of the trial using a digital stopwatch on the operator PC. In order to record natural navigation behaviour, participants were not informed that they were being timed.

4. RESULTS

The three categories of observations recorded in the study will be discussed in separate sections. Quantitative analysis was carried out using IBM SPSS v22. Qualitative analysis was carried out manually, categorising and coding the free-form text into themes which were then summarised.

4.1 Time to complete the navigation task

A repeated measures one-way ANOVA demonstrated a significant effect of travel technique on task completion time ($F_{2,17} = 10.00, p < 0.001$) (Figure 3). The mean completion time was fastest with the Bluetooth controller (50s), and slowest with the magnetic switch (85s). (Inclusion of the participant with PD disease (number 15) did not impact the results and so was retained in the analysis).

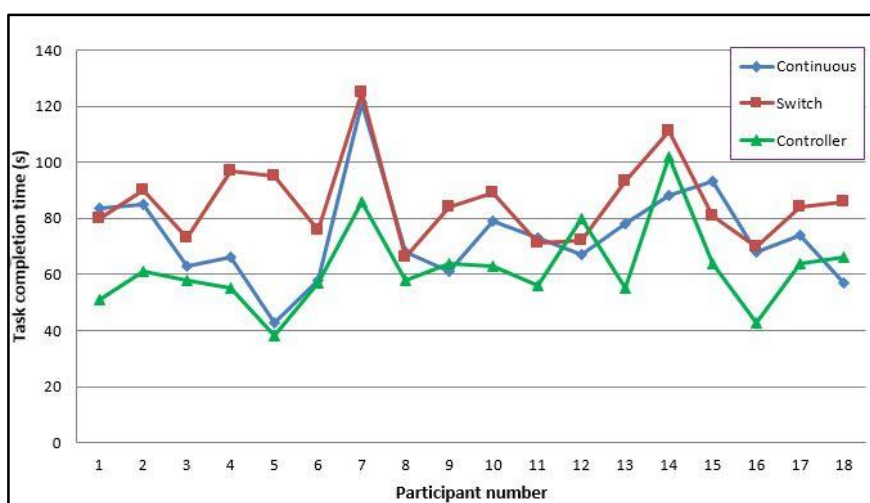


Figure 3 Comparison of task completion times for the three travel techniques

4.2 User experience scores

Participants were asked three questions after each technique (Table 2). Each question was scored on a Likert scale from 1-5.

Table 2. Mean Likert score for each question (StdDev in brackets)

	Continuous	Switch	Controller
Ease of movement (1 = hard, 5 = easy)	3.3 (1.1)	3.8 (0.7)	4.5 (0.9)
Sense of presence (1 = unreal, 5 = real)	3.4 (0.8)	3.1 (0.7)	3.4 (0.7)
Liked the technique (1 = disliked, 5 = liked)	3.1 (1.1)	3.4 (0.9)	4.1 (1.1)

A repeated measures one-way ANOVA demonstrated a significant effect of travel technique on the participants perceived ease of use ($F_{2,17} = 8.41, p < 0.01$) and on enjoyment of the technique ($F_{2,18} = 4.08, p < 0.05$), but there was no significant effect of travel technique on the mini-presence score ($F_{2,17} = 0.90, p = 0.41$).

Post-Hoc analysis revealed that the Bluetooth Controller was easier to use than both the continuous motion [$t(17)=3.61, p=0.00.$] and the switch [$t(17)=3.01, p=0.01.$], but there was no significant difference in ease of use between the switch and continuous motion. The controller was liked better than the continuous motion [$t(17)=2.41, p=0.03.$], but comparison with the switch, or between the switch and continuous, showed no significant difference.

There was a strong positive correlation between perceived ease of movement, and enjoyment of the technique ($r= 0.78$), and a moderate positive correlation between enjoyment and sense of presence ($r = 0.38$), but no correlation between perceived ease of use, and task completion times ($r = -0.19$). There was also a weak positive correlation between ease of use and sense of presence ($r = 0.24$).

At the end of the study, participants were asked to reflect on all three techniques and to compare them. The Bluetooth controller was the preferred travel technique, which was also expressed to be the easiest to use. The continuous motion was both the least liked travel technique, and the one that participants felt was hardest to use (Figure 4).

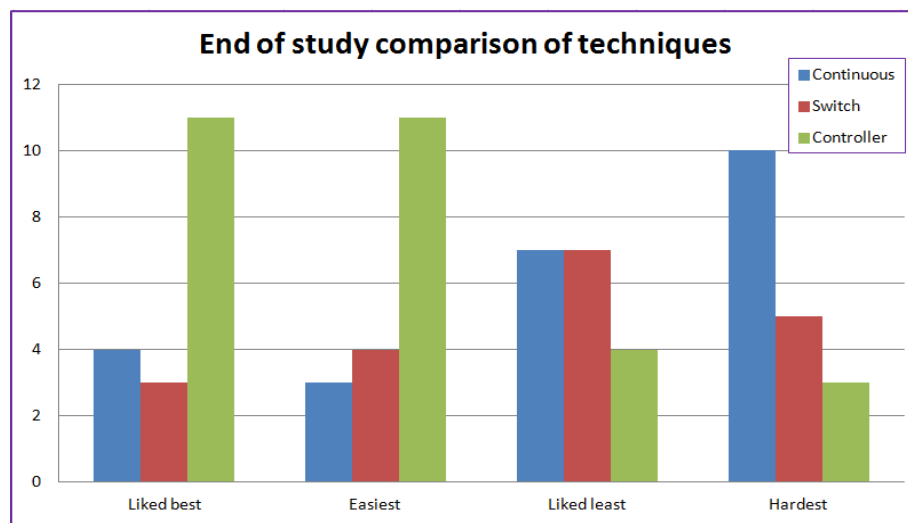


Figure 4. Numbers of participants expressing preferences for each of the three techniques

4.3 Qualitative feedback

After each trial, and at the end of the study, participants were given an opportunity for additional comments on the travel techniques, and these comments were manually coded and categorised to identify common patterns or trends, as well as conflicting opinions. The majority of the responses fell into the broad categories of "control", "discomfort", "ease of use" and "naturalness". Key points for each technique are summarised in individual sections below.

4.3.1 Continuous movement. With regards to control, 61% of participants expressed dissatisfaction with the lack of ability to slow down or stop. 17% stated that they used collision with obstacles in the environment to help them manoeuvre. In this condition, 39% of participants described some level of disorientation, generally associated with the inability to unlink head motion from the direction of movement, 22% of participants reported some level of dizziness or mild nausea when turning, particularly during sudden or rapid course corrections. For complex movements, 56% of participants highlighted the need to anticipate turns and plan ahead to avoid overshooting the goals, but nevertheless, 50% of them explicitly reported that this condition was intuitive to use, with low cognitive demands and mapping of movement to head orientation freeing them up to plan the route without explicitly thinking about the controls.

4.3.2 Magnetic switch control. The qualitative feedback from this condition was the least consistent, but key factors emerged primarily around the location and responsiveness of the switch. 33% of participants felt that the switch gave them greater control over their movement, but others noted that on some occasions they either forgot to use it, or made a conscious decision to ignore it. The magnetic switch technique is known to have both false positives and false negatives (Smus & Riederer, 2015), and together with the small delay between sliding the magnet and the movement response caused 61% of participants to report dissatisfaction with the responsiveness

of the control, leading to overshooting of targets and the need for error correction. The inability to control the speed or to reverse or sidestep was reported as a problem for 33% of the participants.

Nearly half of the participants expressed dissatisfaction with the location of the switch, with some feeling the need to hold the headset in place when using the switch, and reports of fatigue and aching in the arm due to prolonged elevation. The switch was felt to be a very unnatural way of controlling movement, with the distinctive sound, and the need to raise the hand to the head to stop or start motion being reported by 50% of participants as factors which diminished their sense of immersion or presence.

4.3.3 Bluetooth controller. The controller received considerable feedback, but much of it was conflicting. The level of control of movement was generally considered to be good, with 72% reporting that the controls were responsive, and that the ability to stop, start and reverse were important features. However, 40% of the participants described some level of mismatch between their expectations of the control and the actual experience. This mostly related either to the lack of strafing (right and left side steps), and to the need to use the head to control direction but the controller for speed. Some participants explicitly described this as making them have to consciously think about how to move around, however overall, 67% expressed satisfaction with the ease of use. 'Naturalness' was quite a polarised category, with positive comments generally relating to prior experience or intuitive use, and negative comments relating to less immersion, and to the mismatch between expectation and experience. Half of the participants felt that this was the least natural and intuitive way of moving around, even if they found it the easiest to use. Interestingly, the participant with Parkinson's Disease particularly liked this technique, and felt that it was less effort and offered "more control than I usually have with tasks".

4.4 Additional observations

Whilst there was no explicit remit in this study to record observational data, there were some recurrent behaviours worthy of note.

4.4.1 Movement of the body. There was a distinct difference in the body movements of almost all the participants depending on the technique in use. When using the handheld controller, they generally remained upright and fairly still, using their feet to turn the chair when changing direction, but otherwise showing little movement of the torso. In contrast, when using the other two techniques (and particularly the continuous motion), most participants involved the whole body in the interaction, tilting, turning and twisting the torso and leaning the head in response to anticipated changes in direction.

4.4.1 Frequent stopping. When using either of the controls which had the ability to stop the motion, many participants elected to stop movement for every change of direction, even in places where they had successfully manoeuvred in the continuous motion trial.

4. DISCUSSION

The performance and graphical fidelity of Google Cardboard techniques cannot compete with more expensive VR solutions, but it has the huge advantage of allowing the wider patient population to access truly mobile VR with minimal financial outlay. However, the quality and enjoyment of these first experiences could, for many patients, significantly influence their desire to engage with VR in the future. Furthermore, badly designed interactions may even hinder or undermine rehabilitation goals.

Whilst the findings of this preliminary work are based on a relatively small and heterogeneous group of participants and should be interpreted with caution, they do give some useful insight into the user experience, and offer some guidelines which may be useful to consider when designing mobile applications for virtual rehabilitation.

First and foremost, it is important to remember that we may have little control over the type of headset which is being used. The default position is likely therefore to involve continuous movement, perhaps mediated by head-orientation control or other software-mediated device. In this situation, any requirement to make tight turns or unplanned manoeuvres should be avoided, and a suitable collision boundary provided at points where the user may wish to stop. Whilst in ideal circumstances users should be provided with an independent line of site without changing direction (Doug A. Bowman et al., 2012; Sayers, Wilson, Myles, & McNeill, 2000), this may prove difficult when input options are limited.

The addition of the switch control to the continuous movement increased the time taken to complete the task without greatly improving the user experience. However, the current magnetic switches are not 100% reliable, and it may be that a more responsive switch might bridge the gap between the immersiveness of continuous movement and the ease of use of the handheld controller. With the recent release of Google's version 2 headset it will be interesting to evaluate whether the new capacitive switch will impact these findings. It was notable that this switch

technique was significantly slower than the less controlled continuous motion. Whilst we might have anticipated fewer errors and corrections of direction, this did not seem to be the case, and, furthermore, most users chose to stop and turn at almost every location, even if they had previously navigated them smoothly using continuous motion. However, the unnatural position of the switch on the side of the head, and the implications this has for fatigue and pain, may make this unsuitable for many patient populations. This is of some concern, bearing in mind that a number of VR headsets currently being developed are planned to incorporate a number of headset-mounted controls.

Bluetooth controllers are available at very low cost, and indeed are often included with the purchase of a headset. For many users, particularly gamers, this provides a natural control, but it was reported to create a disconnect between the user and the virtual environment. However, this method was the most efficient for task performance, being nearly 50% faster than the magnetic switch control. This result is likely to vary with different navigation tasks, but is a significant factor, particularly where efficient maneuvering is required in an unfamiliar environment. When combined with head-orientation for direction selection, this technique appeared to have the highest cognitive load, and it may be necessary to use the controller for both direction selection and velocity control in order to lower the cognitive demands of this technique.

In contrast to reported immersion scores, we observed that the physical behaviour of the participants indicated a higher level of immersion when using the continuous controls than with the Bluetooth controller, and this warrants further investigation as it may have implications for certain types of application. Where increase immersion is desirable, for example in exposure therapy, then a hand-held controller may detract from this. However, the increase in movement of the torso and head, may increase the risk of injury or falls, and this is a significant consideration for many patient populations, particularly where there is already compromised balance.

In summary, none of the three techniques evaluated in this study offered an ideal solution for travel within mobile VR, but do point towards some preliminary design guidelines (Table 3). Further work in clinical population is necessary to establish more robust guidelines. In addition, in this study we only looked at task completion time in our objective measures, but for future work accuracy and error rate will be important additional considerations.

Table 3. Preliminary usage indicators for the travel techniques evaluated in the study. The clinical indicators are tentative, as we have not yet tested directly in these populations

	Continuous movement	Switch on headset	Bluetooth controller
Accurate maneuvering	X	X	✓
Increase immersion	✓ ¹	X	✓ ¹
Balance impairment	X	X	✓
Parkinson's Disease	✓	X	✓
Cognitive impairment	✓ ²	✓	X
Avoid cybersickness	X	X	✓
Efficient travel time	✓	X	X

¹Depends on individual user ²for wide area use

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