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Motion matters: Comparing naturalness of interaction with two locomotion interfaces using decision-making tasks in virtual reality

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***Abstract*—Virtual environments can replicate the visual appearance of terrain conditions, but movements involved in using the interfaces confer their own bodily sensations, which can be incongruent with the visual presentation. Assuming that more natural interfaces produce more natural locomotor behaviors, we propose a framework for assessing the quality of a locomotion interface. Using this framework, we studied the interaction of different locomotion interfaces with visual information on wayfinding decisions in a virtual environment. We compared decisions made using a dual joystick gamepad with a walking-in-place metaphor. Paths presented on a given trial differed visually in one of the following aspects: (a) slope, (b) friction, (c) texture, and (d) width. In this experiment, choices made with the walking-in-place interface more closely matched visual conditions which would minimize energy expenditure or physical risk in the natural world. We provide some observations that would further validate this approach and improve this method in future implementations. This approach provides a way of both studying factors in perceptual decision making and demonstrates the effect of interface on natural behavior.**

***Index Terms*—locomotion interface, virtual reality, presence, realism, walking, biomechanics, human factors**

I. INTRODUCTION

A common working hypothesis for those who develop virtual environments (VEs) is that sensory realism facilitates user engagement in VEs and helps to elicit more natural behaviors [1]. To maximize realism, the sensory information and behaviours they demand ought to be as close to natural environments as possible [2]. While it is well established that the quality of visual stimuli is a key factor influencing the quality of interaction in VEs, without similar high-fidelity information from other senses such as that of touch, how naturally can we expect users to act in a virtual reality environment when tasked with finding a path towards a goal?

Moving from one place to another naturally involves multiple sensory systems. Vision, vestibular sensation, proprioception and somatosensation play complementary roles in walking. Strategies for balance while walking, running and standing are classified as being either proactive or reactive. Proactive balance control mechanisms involve locomotor planning [3]. As vision works from a distance, vision detects possible paths or obstacles, [4], and also provides information on self motion through optic flow [5]. Vestibular senses also contribute to provide information about a walker's displacement, acceleration and heading [4] and thus also facilitate feelings of self motion [6].

In contrast, a reactive strategy for walking is employed to confirm the success of proactive strategies, or serve to correct locomotion once proactive controls fail [3]. Vestibular sense, can also play a role in reactive balance. As an example, the vestibular system would register the tilt of the head as the body moves away from the desired movement. Somatosenses offer information about the body's contact with surfaces [7]: specifically the form and texture properties of stepping surfaces, control of the grip of the foot soles and toes [8], and thus could convey a slip on the ground. Proprioceptive senses provide information on limb position and movement and compensate for position changes and movement in order to maintain bodily stability [8], thereby providing the location of the limbs as the falling walker recovers [3].

Thus, if both the visual presentation and the activation of a walking interface are natural and compelling, we might expect locomotion behavior to be similarly realistic; when a person visually identifies potentially troublesome terrain, we could expect that their response is to avoid the terrain if possible. However, though VEs can replicate the visual appearance of terrain conditions, they have yet to produce a locomotion interface that is capable of convincingly simulating the multimodal and complex information accessible to the bodily senses [9]. The movements involved in using even the most advanced locomotion interfaces will confer their own bodily sensations distinct from the visual presentation. It stands to reason, then, that existing locomotion interfaces, with

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differences in physical usage and thus different limitations might affect navigation decisions such as the optimal path to a goal.

In this work, we compare two locomotion interfaces and their effect on visual decision-making in VEs. Questions driving this project include the following: (a) To what extent is a person's locomotor plan influenced by visual information or by the movement demanded by the locomotion interface? (b) What is the role of visual information in path planning? (c) What is the importance of economy of movement or perceived risk to a person in a VE? Here we provide a framework to study these questions in virtual reality.

II. Related work

The implementation of an interface that "feels" natural and elicits natural behaviour is desired for many applications – such as for psychological testing or therapeutic and clinical purposes. Various means have been proposed as a way of investigating how much sensory realism an interface provides. Some of the most compelling examples of these are papers attempting to measure presence, immersion and flow – cognitive and psychological phenomena strongly correlated with sensory realism and natural behaviour. These include questionnaires, physical measures, and task performance studies.

Questionnaires are a straightforward approach to measuring naturalness considering that what feels natural can be strongly subjective. Examples of this include a sixty-one item presence questionnaire categorized into three sub-scales by Witmer et al. [2]. Unfortunately, the design of a questionnaire or the way a question is posed requires great care to avoid any potential ambiguity of terms or of expectations. As an example, the terms "realism" and "immersion" can be conflated. Thus, the reliability of the questionnaire or testimony could be suspect. Moreover, the rating scale might be internally consistent, but not externally meaningful [10].

If objectivity is desired, then physiological measures such as heart rate and galvanic skin responses can be used to infer the users' engagement with the VE [11]. Higher frame rate and lower latency reportedly increased users' heart rate during simulations of stressful situations such as falling from a dangerous height [12]. Major limitations to assessing interfaces in this way are the intrusiveness of the techniques, reliance on extreme scenarios and often complicated machinery to transduce and record the measures. In addition, studies indicate that some interface devices produce measurable physiological signals only in stressful or extreme situations [13].

Other researchers have attempted to develop behavioural-based measures of naturalness. In particular, some studies investigating locomotion interfaces have emphasized a user's task performance. Approaches such as these may use a number of variables such as speed and accuracy in reaching a walking target. Ruddle et al. tracked collisions with obstacles in the environment [14]. Other studies take a high level task approach, such as having participants navigate a virtual landscape from waypoint to waypoint [15]. Unfortunately, the process of data gathering and analysis for task performance may be complex. Another possible issue arising from task performance studies is that the results may not be broadly generalizable. Football maneuvers seen in a study by Williamson et al. are hardly generalizable to all real life locomotion settings or untrained individuals [16]. The goal, then is to design tasks which are simple in their analysis and as broadly applicable as possible.

The framework proposed here was to an extent inspired by similar studies on pathfinding in animals such as anoles and ratsnakes [17], [18]. Animal studies are helpful insofar as they can provide starting points for the purpose of creating a testing framework which offers simple and intuitive results. The animals were given a number of different routes to choose from with different properties. Alternatives that make it easier for the animals to stabilize and move are chosen more frequently than not. Anoles preferred perches with wider diameters and thus more surface area so that their toes could more easily grip them and launch them to the next platform. Snakes, having no limbs, and moving only with belly scales, preferred surfaces with fewer gaps between them and preferred straight passages as opposed to those with a 90-degree turn.

In this paper we consider a comparison method for assessing the success of an interface. As a measure we use the conformance of behavioral choices with expectations of natural real world behavior. We test the hypothesis that the interface which produces natural behaviour more frequently or reliably is therefore more realistic to the user. We assess this by comparing choice responses with a "traditional" gaming interface with a more immersive VR locomotion technique.

III. Methods

We compared participants' behaviour using a "traditional" interface and a VR specific interface that attempts to emulate natural walking. To understand how visual path information and locomotion interfaces influence decision making in virtual worlds, we built a series of virtual rooms, each with two pathways leading to two goal choices. Participants, using either a joystick or a walking-in-place (WIP) metaphor, walk to a goal. The interface which produces natural behaviour more frequently or reliably is considered more successful than the other. The task was designed, rendered and conducted using Vizard 5, a Python/OpenGL-based toolkit (https://www.worldviz.com/vizard-virtual-reality-software.) Some of the models were made using a combination of 3ds Max® v. 17.0 by Autodesk (https://www.autodesk.ca/en/products/3ds-max/overview) and Blender v. 2.76 (www.blender.org).

The images were displayed on a eight-projector quasi-spherical curved screen referred to as the "Wide-Field Immersive Stereoscopic Environment" (WISE) that fills a user's visual field. The user was positioned inside a indentation in the bottom middle of the system, centering their head in the display. The environment was rendered by a computer cluster consisting of a single master node and 8 client nodes running Nvidia Quadro 4000 graphics cards. We chose to use a projected display, as most available head-mounted displays have limited resolution and will obscure a participant's real

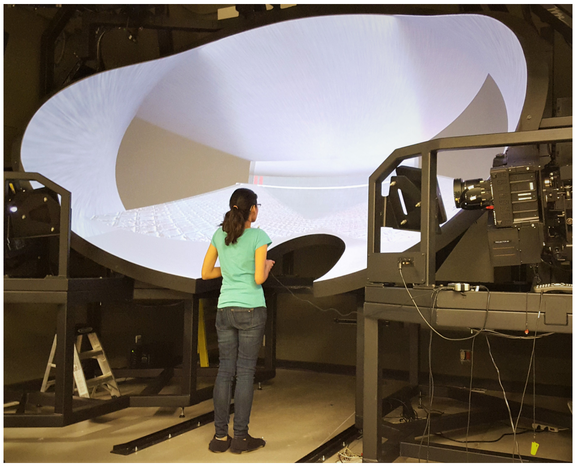

Fig. 1. A participant using the joystick interface. In the actual experiment the room lights were extinguished and only the display was visible.

body, increasing the likelihood of colliding with real world objects or losing balance [19].

All participants used both interfaces in separate blocks of trials. For each trial, participants moved their avatar from a starting position towards one of two goals in the virtual room requiring them to make a choice between two paths to complete the trial. Each path consisted of a plank raised above the ground, approximately 40 meters in length. The goals were marked by a red door which opened when the participant was in close proximity. The room would reset itself when the participant moved through the door, whereupon the participant was relocated to the starting position in the new room and a new condition was randomly chosen. If a participant were to step off the offered paths, they were transported back to the starting position and the misstep recorded. The participants were told to make their decision and walk as quickly as possible as walkways in any given trial could disappear, with the chance increasing exponentially as a proportion of time.

The two path choices differed in one aspect per trial. These aspects were: (a) slope: straight or going upward, (b) specularity: shiny or matte, (c) texture: rubber, stone, gravel, (d) width: wide, medium and narrow. Each pair of comparisons within each aspect was tested twice, with the path conditions flipped between left and right paths. (For example, both left: shiny, right: matte and left: matte, right: shiny were tested for each locomotion interface and each user). Locomotion interfaces used were joystick control and a WIP metaphor tested in separate blocks – that is, one block for each of the two interfaces with each block consisting of 16 trials, totalling (16×2) 32 trials. The order of trials within a block was computer-randomized and block order was counterbalanced to control for ordering effects. Path condition, choice, and locomotion interface were recorded as data.

To assess the possible biases stemming from individual aptitudes and preferences, participants were given a modified multiple intelligences inventory containing a subset of the questions measuring only kinesthetic and visual-spatial scores [20], [21]. The results of the inventory were used as a co-variate. Given the ubiquity of video gaming, we assumed that at least some participants had a degree of familiarity moving around with more common video gaming interfaces such as the joystick used in this study. Therefore, participants were asked questions about gaming habits (Table I); specifically whether they regularly and/or recently played games, and what sort of games they played. For the purpose of this study, participants who answered at least somewhat often on either questions 2, 3 or 4 were considered "gamers." To clarify, we defined "often" as being on a weekly to semi weekly basis, and specified only for games presented in a 3-dimensional perspective.

Participants were briefed on all requisite safety procedures and their rights prior to the experiment, asked to fill in the multiple intelligences inventory described above and answer the video gaming questionnaire in Table I. A coin was flipped to decide which of the interfaces they would use first – heads: joystick, tails: WIP. Their instructions were to use the interface to navigate to either one of the red doors at the end, and to do it as quickly as possible, as the walkways would disappear from underneath them at random, with the likelihood that it would disappear increasing as time went on. After each interface block, participants answered the five questions about their experience with each interface implementation.

The results of the experiment were analyzed using the MATLAB (2015a) computing environment, and its Statistics and Machine Learning Toolbox.

Details on the conditions, both visual path conditions and locomotion interface conditions are in the following section.

A. Path conditions

Conditions were (a) slope: 20 degrees upward and straight (b) friction (as indicated by specularity): shiny or matte, (c) textured: rubber, stone, gravel, (d) width: wide, medium and narrow. These conditions were chosen primarily based on their ease of implementation in the VE and are not intended to be exhaustive or considered factors in and of themselves.

1) Slope condition: There are two phases to stepping on a level surface: a positive work phase, which roughly correlates to the lift and acceleration of the body's center of mass. This is counterbalanced by an equal in magnitude negative work phase in which the body's center of mass is moving down and decelerating. When walking uphill, the work in the negative phase decreases with the inclined ground while the positive increases to make up for the increased vertical distance [22].

TABLE I
VIDEO GAME QUESTIONNAIRE, ON A 5-POINT SCALE

1) Do you play video games? (yes/no)
2) How often do you play isometric/top-down viewpoint games?
3) How often do you play first person viewpoint games?
4) How often do you play quasi-first person view point games (i.e. over the shoulder shooters)?
5) How often do you play games that are not represented in the above three categories?

Thus, as incline increases after a threshold of roughly 10% [22] the metabolic costs of walking uphill go up. With this in mind, the path was inclined either 20 degrees upwards from the starting position, roughly correlating to a 25% incline or level (a 0% incline). It was expected that most users would prefer the level path, as walking uphill in the real world increases energy expenditure. At this time, we did not test downhill slopes. For trials where the slope condition was not being tested, both paths were level. Paths were the same length, whether inclined or not. Figure 2 shows an example of how this condition appears.

2) Specularity condition: Stepping on a low-friction surface is inherently risky for tall bipeds with high centers of gravity such as humans. During a step in bipedal walking, the sole of one foot supports the center of mass while the other leg lifts off the ground [3]. The step completes when the center of mass is again evenly distributed between the two feet. Low-friction surfaces increase the likelihood that either of the feet could slide from failing to adequately grip the walking surface, thus increasing the risk of falls [23]. Greater specularity conveys a lower amount of friction to be expected on the walking surface, similar to the appearance of ice or water on the ground [24]. Strategies for minimizing risk on slippery surfaces usually involve maintaining the center of mass lower during locomotion, reducing step velocity and shortening the length of a step [23]. These accommodations decrease the metabolic efficiency of walking [23]. For this testing condition, a path was either shiny, with a specularity of roughly 30% or matte, with no specularity. Where the friction condition was not tested, the default texture was matte. The image above provides an example of one of these trials (Figure 3).

3) Texture condition: Ground texture provides information about how stable and compliant the walking surface is. Shifting and uneven ground means more muscle activation in the knees and ankles for stabilizing the body, and consequently, increased energy expenditure [25]. Maintaining adequate toe-to-ground clearance when ground height varies too greatly forces variable timing of steps, which unbalances the energy exchanged between the positive work phase and negative work phase of stepping [26]. For a compliant, unstable surface, we selected a gravel texture. A stone surface is uneven, but is not unstable. The default rubber ground texture was also used. Figure 4 shows an example of the texture condition with gravel and rubber. We expected that the gravel condition to be the least favored, stone to be favored more than gravel, and rubber favored above the others.

4) Width condition: Bipedal motion imposes unavoidable side-to-side instability when redirecting the center of mass laterally from the standing leg onto the swing leg. Thus, during normal unconstrained walking, humans will step with their feet placed roughly 12% of a leg length apart, which provides the best compromise between efficient walking and lateral stability [27]. The trade-off with a narrower step width, is that the stepping leg needs to move laterally to avoid the standing leg while counterbalancing and maintaining the center of mass within the bounds of the base of support lest they fall off the path [28]. For this experiment, paths were either wide, moderate or narrow. At a narrow enough width, participants were expected to spend more effort consciously trying to maintain equilibrium on the path. Therefore the narrow width path was expected to be favored the least, with mid-width paths favored more than narrow. The wide path was predicted to be favored at least as much as the mid-width path, if not more, due to the larger margin of error for a participant's foot placement. The example image is of narrow and wide path choices (Figure 5.)

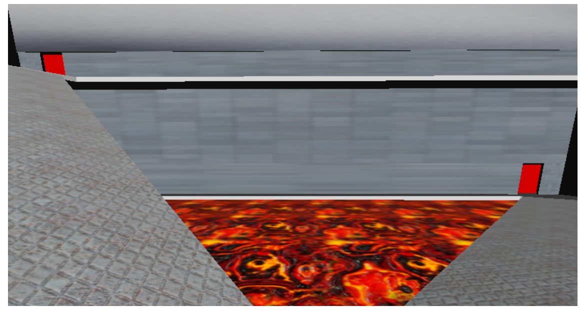

Fig. 2. Example of an slope condition trial

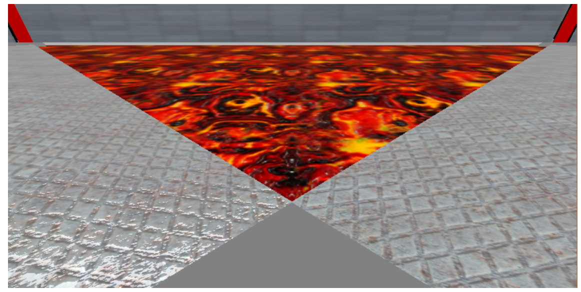

Fig. 3. Example of a specularity condition trial

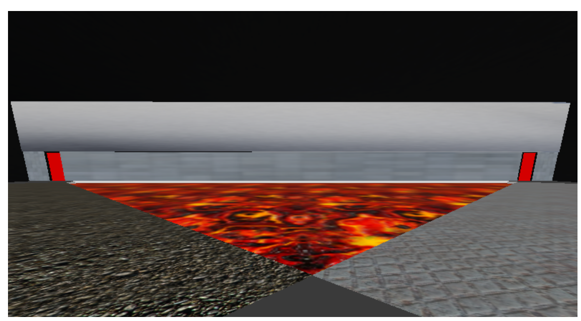

Fig. 4. Example of a texture condition trial

B. Locomotion interfaces

The locomotion interfaces tested were joystick control and WIP metaphors. The relative success of the interface was determined by the proportion of trials that users select the more natural path choice.

1) Joystick: Joystick control, as mentioned above, is sometimes called '"joystick flying" in the literature due to its similarity to how one would feel as if standing on a flying carpet

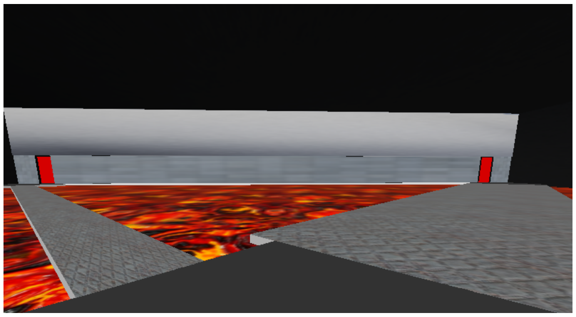

Fig. 5. Example of a width condition trial

[5]. This locomotion type best represents what is currently the most ubiquitous locomotion control in home entertainment, but offers little to no realistic somatosensory, proprioceptive or vestibular feedback. We expect this locomotion interface to perform poorly relative to the other in terms of naturalness of locomotor decisions. The joystick used for this experiment was a Logitech dual analog joystick, meaning that two small joysticks are controlled with either thumb. Pushing the left joystick forward provides a variable-speed forward translation. Variable-speed orientation (pitch and roll), including left-right steering is controlled using the right joystick.

2) Walking in place: Walking-in-place metaphors offer greater proprioceptive and somatosensory similarity to natural walking than joystick control. However, the user simply steps in place and there is no forward movement between feet during striding and also little in the way of vestibular feedback.

Fig. 6. Markers placed on the feet track foot speed, which determines the user's translation speed in the VE.

The WIP metaphor was an implementation of the stepping-in-place approach described in [29]. Forward translation speed was determined by the user's foot speed – the faster the feet moved, the quicker the user traveled in the VE. Trackers were placed on the toes of shoe covers which were then fitted over the participant's feet and were tracked in six degrees of freedom using an OptiTrack V120:Trio infrared motion sensor array set in front of the feet (see Figure 6 for details.) In a divergence from the original implementation, instead of using the rotation of the torso (via trackers placed on the hips) to change direction, the direction of translation was determined by the angle of rotation of the user's head (see Figure 7 for details.) This was accomplished by using WorldViz PPT head-tracker markers located on either side of 3D shutter glasses. For this experiment, we only used the glasses for tracking and did not present stereo images. The infrared sensors for head tracking were located on the top of the screen assembly.

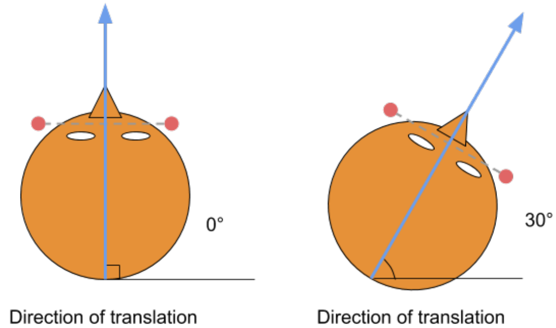

Fig. 7. Markers located on either side of the head track head rotation. Direction of translation is perpendicular to a straight line drawn between the markers.

IV. Results and Analysis

In total, 31 participants were recruited by word of mouth in the university community, though 6 data sets had to be excluded due to equipment error. The final analysis includes data from 26 participants (15 male, 11 female, mean age 29 years, SD = 10.4.)

A. Statistical Model

To restate the hypothesis, the responses are expected to be natural more often in the WIP interface condition than in the joystick condition, across all visual conditions. Because the users either chose the expected response for each condition or not, the response data is binomial. This motivated our use of generalized linear mixed model analysis to model the likelihood of choosing the expected path as a function of the independent variables. The experiment was a repeated-measures design and hence we included the subject as a random effect. This accounts for the repeated measurements and modeled individual differences, given the highly personal nature of experience.

Visual condition, interface, and side (the side of the expected path), were independent variables included in the modeling. Visual condition was coded by the type of comparison made (e.g., texture differences or friction). Interface was either joystick or the WIP metaphor. Side bias, a participant's tendency to select one side or another, was noted during the experiment – In particular, participants preferentially selected the path on the right hand side by a ratio of 29:23. To model this, we introduced a variable, side, that was coded "0" when the expected response was on the left and "1" when the expected response was on the right.

For the dependent variable, we compared the participants' responses to the expected responses to each trial based on putative energy expenditure. We predicted that participants would choose paths exhibiting conditions that in the real world, would minimize energy expenditure more often using the WIP metaphor when compared to using the joystick. For each participant on each trial we recorded whether the response matched the metabolically preferred response or not.

Other participant data: age, sex, gaming/non-gaming status, visual kinesthetic scores, and subjective ratings were collected and treated as confounding variables in our analysis. Participants were deemed gaming if they recently and regularly played 3d perspective games and non-gaming if they did not. The visual-kinesthetic score was tallied from a subset of questions from the multiple intelligences questionnaire and recorded as the difference between the two categories.

B. Model Fits

Starting from a full model, F-tests ruled out age ($F[1, 818] < 0.001, p = 0.99,$) gender ($F[1, 818] = 0.049, p = 0.826,$) gaming/non-gaming status ($F[1, 818] = 0.047, p = 0.828,$) visual-kinesthetic scores ($F[1, 818] = 0.424, p = 0.515$) and subjective ratings ($F[1, 818] < 0.5, p = 0.387$) as significant effects and were thus dropped from the model.

With these variables eliminated, we were left with a base model that included visual condition ($F[3, 818] = 17.53, p < 0.001$), interface ($F[1, 818] = 6.17, p = 0.01$) and side bias ($F[1, 818] = 12.17, p < 0.001$) as fixed effects, and the subject random effect ($SD = 0.274$, 95% CI of [0.123, 0.606].)

Interactions between the independent variables were ruled out using comparisons of the Akaike and Bayesian information criteria (AIC and BIC,) which are methods of estimating the likelihood that a given model will produce the values observed. Candidate models that included one of the following two-way interactions were assessed relative to the base model: interface and visual condition (coded IV), interface and side (IS), side and visual condition (SV). Model quality is indicated by lower AIC and BIC scores. Of these candidate models, AIC scores did not favor IV and SV ($\Delta AIC_{IV} = 2.4$ and $\Delta AIC_{SV} = 6.1$) with IS lower, but only marginally so ($\Delta AIC_{base} = 1$). However, the base model scored favorably on BIC across the board ($\Delta BIC_{IV} = 15.6$, $\Delta BIC_{IS} = 3.7$ and $\Delta BIC_{SV} = 19.3$). Given that these models with interactions were not significant improvements over the base model ($\Delta df_{IV} = 3, p_{IV} = 0.2$, $\Delta df_{IS} = 1, p_{IS} = 0.08$, $\Delta df_{SV} = 3, p_{SV} = 0.82$), the base non-interaction model (visual condition, interface, side bias fixed effects, and subject random effect) was selected as the final model on the basis of parsimony.

In the next sections we will describe the nature of the main effects of these factors.

C. Interface considerations

In hindsight, the WIP condition was limited in its capacity to simulate realistic walking primarily in the turning agility afforded to users. It was relatively easy for those who wished to turn 180 degrees without displacing themselves using the joystick, but the same maneuver was not possible in WIP. This difference in maneuverability may have affected the decisions of some participants. Efforts were made to reduce the amount of steering participants needed to do on any given path, but nonetheless, participants occasionally needed to adjust their heading. Thus the similarity to real world walking may have thrown off participants when they encountered difficulty turning in place. In addition, our implementation of WIP used head-directed motion, which is known to be sub-optimal for producing realistic locomotion, as shown in the detailed analysis by [30]. This implementation was chosen because of current limitations in available resources. In the future, we may be able to mitigate such an effect with more effective design of the walking interface.

The analysis above indicated that interface played a moderately significant role in determining participant choices of path (See Figure 8 for the average results per participant fitted to model predictions). Overall, participants were somewhat more likely to select the more natural response when they used the WIP metaphor as compared to when they used the joystick (48.6% of the time using joystick, 56.7% of the time using the WIP metaphor).

Participant-to-participant, the proportion of expected responses ranged more widely with the joystick interface than with WIP (maximum 0.81 and 0.75, minimum 0.25 and 0.31 for joystick and WIP, respectively) with the median proportion of expected responses being somewhat higher with the WIP condition at 0.56 compared to 0.44 for the joystick (See Figure 9).

The time it took for users to reach their goal did not significantly differ between interface conditions.

D. Differences in visual conditions

According to the model, visual condition played a highly significant role in participants' choices (see Figure 10). To visualize how the type of visual condition mattered in selecting the expected response, we averaged the participant's responses and grouped them by visual condition type. We then conducted

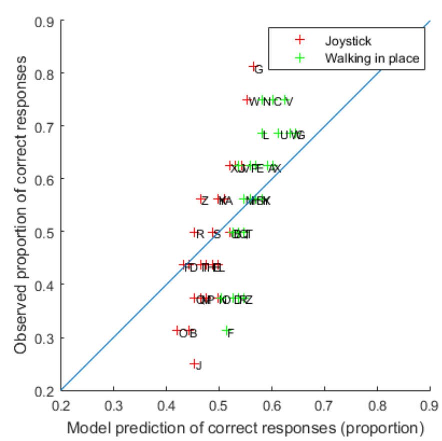

Fig. 8. Mean proportion of correct responses fitted to model predictions, data for both interfaces, 26 participants, labelled A-Z

four separate t-tests (one per visual condition type) comparing joystick and WIP metaphor results.

Based on this analysis, using the walking in-place condition ($M = 0.763, SD = 0.158$) was more likely to result in participants taking the ecologically expected path compared to joystick ($M = 0.603, SD = 0.2$), but only when width conditions were presented ($t(25) = -3.503, p = 0.002$). However, there were no real or virtual consequences to most of the visual conditions, most of which would have been threatening only because of previous experience walking in the real world. It stands to reason that participants, during the path width condition, were responding to the threat of navigating off platforms rather than the admittedly hollow threat conveyed by other visual presentations.

For texture ($t(25) = 0.782, p = -0.442$) and friction visual conditions ($t(25) = -0.778, p = -0.444$), walking-in-place seems marginally more likely (texture:$M = 0.468, SD = 0.216$; friction: $M = 0.5, SD = 0.4$) to elicit natural path choices than joystick (texture: $M = 0.426, SD = 0.212$; friction: $M = 0.423, SD = 0.366$), though not to a significant degree. It is possible that the quality of the textures and the accuracy of the visual conditions may account for discrepancies between expected outcomes and the actual experimental results.

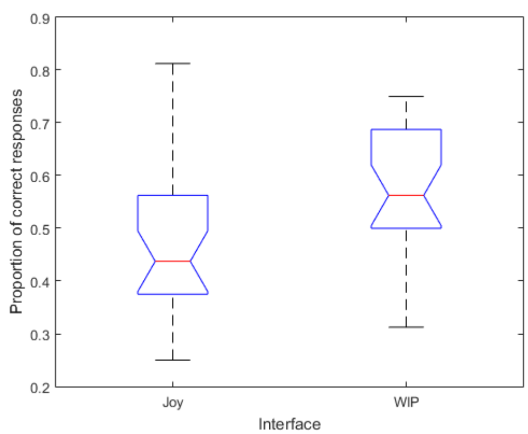

Fig. 9. Effect of interface on path choice. Proportion of correct responses per participant, grouped by interface. Red line represents the median, box is the upper and lower quartiles and the whiskers are the range.

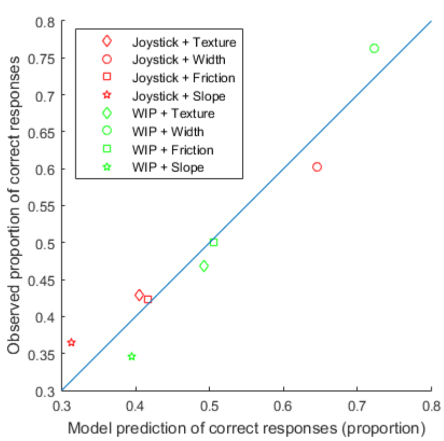

Fig. 10. Mean proportion of correct responses fitted to model predictions, symbols indicate all data organized by visual condition

Furthermore, many participants enjoyed the novelty of effortlessly walking uphill slope because there was no increased effort required to traverse the path. This may account for the slightly lower proportion of expected results for walking-in-place (M = 0.346, SD = 0.419) compared to joystick (M = 0.365, SD = 0.414) during slope condition presentations, though these were again, insignificant (t(25) = 0.328, p = 0.746). Interestingly, pairwise t-tests between the combined conditions indicate that falls differed between the interfaces when slope was presented, t(25) = -3.07, p = 0.005 (Holm-Bonferroni corrected). The unexpected results for WIP and the falls might indicate more risk-taking behaviour in the slope condition.

The results here indicate that experiments using this paradigm should take care to impose suitable (in terms of experimental goals) in-environment penalties in order to provide some balance between the risks implied by the visual conditions and their impact in the VE.

E. Side bias

A participant was more likely to select the natural choice if the path was on their favored side. Participants in our experiment preferred the right path during the joystick condition 58.65% ($\pm$6.5%) of the time, and the right path during WIP by a ratio of 52.88% ($\pm$4.9%) of the time. Based on this finding, future studies using the two-choice path set up should record participant's handedness data, or at minimum, be expected to adequately deal with a bias after gathering data.

V. Discussion

Early in the development of the study, it was suggested that the validity of the paradigm could be tested by having participants walk to the goals in a real life environment, and comparing the results with those found in the VE, but this was considered not feasible. Given characteristics of the virtual environment, we would have to concede some similarities in favor of participant safety and the practicalities of a real-world space.

This paradigm can be expanded by taking bio-mechanical measures in addition to recording whether or not participants select the expected path. Though users may not choose the ideal path, they may alter their gait or posture under different conditions [31]. This would not be difficult to achieve with the proper motion tracking system setup.

The results of the study provide evidence that different locomotion interfaces elicit different user behaviours, thus reinforcing the importance of considering senses and expectations in addition to and in conjunction with visual stimuli. In particular, what is appealing about this method is the simplicity of obtaining and analyzing the data obtained across two or potentially more interfaces. The most straightforward engineering or industry application would be a tool for benchmarking locomotion interface designs.

Though the immediate aim was to produce a "goodness test" for locomotor interfaces, this framework may have applications in more theoretical aspects of cognition and perception: the findings may be useful in applications not only in engineering and psychology, but can be used to inform methodologies or practices in other fields.

The appeal of studies utilizing virtual reality lies in the investigator's ability to better manipulate the environment than in real world laboratories. A simple test like the one suggested in this paper could provide a greater degree of confidence in the ecological validity of experiments done using certain interfaces over others. Potentially, the paradigm can be used in conjunction with real world testing in order to evaluate experimental methodologies and equipment configurations in behavioural studies.

The relative strengths and weaknesses of different interfaces can be evaluated to select appropriate locomotion controllers for virtual reality studies in behavioural, biological and medical sciences. Architects or civil engineers aiming to implement virtual tours or simulations of their design space may also see value in this work as well.

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