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LoCoMoTe – a Framework for Classification of Natural Locomotion in VR by Task, Technique and Modality

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Abstract—Virtual reality (VR) research has provided overviews of locomotion techniques, how they work, their strengths and overall user experience. Considerable research has investigated new methodologies, particularly machine learning to develop redirection algorithms. To best support the development of redirection algorithms through machine learning, we must understand how best to replicate human navigation and behaviour in VR, which can be supported by the accumulation of results produced through live-user experiments. However, it can be difficult to identify, select and compare relevant research without a pre-existing framework in an ever-growing research field. Therefore, this work aimed to facilitate the ongoing structuring and comparison of the VR-based natural walking literature by providing a standardised framework for researchers to utilise. We applied thematic analysis to study methodology descriptions from 140 VR-based papers that contained live-user experiments. From this analysis, we developed the LoCoMoTe framework with three themes: navigational decisions, technique implementation, and modalities. The LoCoMoTe framework provides a standardised approach to structuring and comparing experimental conditions. The framework should be continually updated to categorise and systematise knowledge and aid in identifying research gaps and discussions.

Index Terms—Human-Computer Interaction, Machine Learning, Navigation, Redirected Walking, Virtual Reality

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1 INTRODUCTION

A prominent issue of Virtual Reality (VR) interaction regards the well-discussed ‘locomotion problem’. This problem occurs when the virtual environment (VE) is substantially larger than the boundaries of the tracked space in the real world [1], [2], [3]. A range of locomotion techniques can address this problem, from controllers to redirected walking (RDW) [4], [5], [6], [7]. The focus of the current paper is on RDW. Therefore for further information on the strengths, weaknesses and applicability of VR locomotion techniques, see the following sources [6], [8], [9], [10], [11], [12].

RDW is an algorithmic solution of “*Natural Walking*” (the aim of which is to mimic the experience of real walking in VR) that allows users to translate physical walking in the real world to large VEs [6] and is argued to provide a greater sense of presence [13]. However, to address the locomotion problem, RDW algorithms introduce manipulations or deceptions to alter a user’s walking behaviour [14], [15]. For example, by applying ‘gains’ (translation, curvature, bending and rotation) to the user's virtual viewpoint. A simple example is that to follow a straight path in the VE, a user must walk a curved path in the real world [11]. There are four main types of RDW algorithms (scripted, reactive, predictive and resetting) [11], each sharing common goals: prioritise the user’s safety [15] and minimise reset techniques to enhance immersion in VR [16]. Two frequently discussed RDW algorithms types are reactive and predictive. *Reactive algorithms* guide users towards a particular area of the tracked space [11], [14], such as ‘Steer-to-Center’ (S2C), which selects gain values dependent on prior and current positional data guiding the user towards the center of the tracked space [17]. In comparison, *predictive algorithms* comprise varying information regarding positional data alongside the user’s future possible directions and thus apply suitable gains for redirection [11], [14], [17].

RDW research is often focused on the continued development of RDW algorithms and thus may explore ‘gain’ perception through live-user studies to improve feelings of immersion and naturalness [14]. Simulation-based experiments can be used to develop new RDW algorithms, mainly through reinforcement learning (RL; a

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branch of machine learning) [13], [15], [16], [18], with promising results compared to commonly used RDW algorithms such as S2C [16], [18]. In addition, simulation-based experiments can address time and money constraints typically associated with live-user experiments [17]. Such experiments can also address issues with predictive RDW algorithms and computational times [16] by producing a large number of simulated paths [13], [19], either through procedural path generators [20] or user path data [15], [21]. However, while simulation experiments are useful analytical approaches, they must continue to support live-user studies and should not replace user experiments [17]. This raises the question: How can we effectively use these two methodological approaches of simulations and live-user experiments to support one another and advance the field? This question reflects an area of discussion not limited to RDW research [22], [23].

A starting point is to consider the current limitations and concerns of RDW algorithms trained through RL. Concerns have been raised regarding environment sensitivity, user tasks within an application [18], and the differences between simulated and real-user paths [19], [24]. Furthermore, recent work by Hirt and colleagues [24], who evaluated real-user path data in 200k simulations, highlighted how sensitive RDW algorithms are to the nuances of walking during user tests, including acceleration, stumbling, and veering [24]. This suggests that minor walking path deviations lead to a negative 'butterfly effect' on RDW algorithms' performance [24].

Consequently, to support RDW algorithms developed through RL, recent research has indicated the need to train intelligent agents on pre-existing path datasets from various user tests [13], [15], [16] and ensure simulated users account for human response to RDW algorithms [20]. Therefore, to support the RDW simulation-based experiments, we must understand how best to replicate human navigation and behaviour in VR [20], which can be supported by the accumulation of results produced through live-user experiments [25].

With this in mind, researchers must identify gaps and conduct further live-user experiments accordingly. At the same time, others may want to identify appropriate training data from existing live-user experiments for simulations. However, it can be challenging to effectively search an ever-growing research landscape for relevant information and thus build upon existing knowledge [23]. Whilst researchers can work individually to build an in-depth knowledge of the literature through systematic reviews [25], this is labor intensive and may result in missing relevant papers [26]. Consequently, we have seen the research community create various taxonomies that define RDW techniques and categorise them based on their design [9], [14], [27]. In addition, Unity-based toolkits with RDW algorithms are also available to be implemented in research studies [28], [29]. Both of these contributions aid the research community by providing an accessible level of understanding through descriptions of techniques and ready-to-implement code. Therefore, the RDW research community may also benefit from a conceptual framework that categorises and systematises knowledge on related concepts [30]. Particularly a framework that categorises live-user experiments to support comparison of experimental methodologies and their influence on user behaviour, helping identify research gaps and pre-existing user-path datasets from various user tasks to train intelligent agents. Therefore, to promote using simulation and live-user experiments in tandem and help build our understanding of how best to replicate human navigation and behaviour in VR, we aimed to create a standardised framework that provides ongoing order and structure to the VR locomotion literature. By categorising the differences in experimental procedures and materials that may produce context-dependent results [31], the aims of the current framework are the following:

1. Facilitate the ongoing structuring and comparison of methodologies giving rise to human movement behaviour in VR.
2. Encourage open science and data-sharing.

The remainder of the current paper critically describes the process and development of the 'Locomotion Categorisation by Task, Technique and Modality Framework' referred to as the 'LoCoMoTe Framework'. It is important to note that the work categorised and presented in this paper is part of an ongoing and dynamic resource and should be community driven and updated accordingly.

2 LoCoMoTe Conceptual Framework

Developing the LoCoMoTe Framework requires an in-depth analysis of multiple studies to account for the ever-growing research area [12] whilst also accommodating the broad range of techniques and modalities and the nature of human behaviour, which is highly dimensional and heterogeneous [32]. Therefore, adopting a high-level analytical approach is appropriate to support researchers in accommodating the comparison of results with varying attributes, such as age and gender [33]. Therefore, while a systematic review is often the methodology of choice due to its association with rigor, reduced bias, and reliable results [34], this was deemed unsuitable for the development of the LoCoMoTe framework due to the focus of systematic reviews on a well-defined research question [35]. In contrast, to support the identification of new research avenues in the future, thematic analysis has been proposed as a more appropriate methodology to group data by identifying categories and patterns [36], [37] [38]. The thematic analysis approach adopted in developing the LoCoMoTe framework initially focused on a deductive approach [39] to provide an analytical overview of the crucial experimental information [39] regardless of individual researcher questions. Themes were created that could be used to identify similarities and differences between user tests and future points of interest to provide an overview of the research landscape. Therefore, the analysis considered the underlying task given to participants that may impact navigational decisions, the locomotion technique and materials used during a study to form a pre-specified conceptual framework consisting of three themes: Navigational Decisions, Technique Implementation and Modalities.

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2.1 Theme 1: Navigational Decisions

The first theme considered the underlying task instructions given to a participant and was related to participants' opportunities to make navigational decisions. We identified that some instructions, such as following a (linear) path, may have no navigational decisions, as seen in the work by Interrante et al. [40]: *"Each participant was asked to travel from one end of the hallway to the other, and back"* page 169, [40]. Other tasks can allow for navigational decisions, such as pick-up 'x' items in a room, as seen in the work by Schmitz et al. [41]: *"Participants had the task to find and collect the highest of five pillars"* – page 1626, [41], and then there is exploration, i.e., where there is no underlying goal that may restrict navigational decisions.

Based upon identifying tasks such as: following a path, finding 'x' items, and exploration, we initially considered task-based instructions on a categorical scale of 1-3 (1 = Restrictive, 2 = Task-Based and 3 = Explorative). However, having only three categories was limited, as not all paths will be solely linear. Some may contain junctions and thus allow for navigational decisions. Therefore, to account for tasks that may fall somewhere between, we extended the task-based instructions categorical scale to 1-5 (1 = Restrictive, 3 = Task-Based, and 5 = Explorative) (Fig. 1).

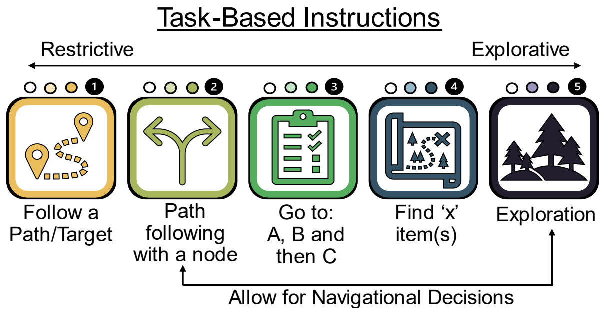

Fig. 1. Navigational Decisions Categorical Scale: ranging from 1-5

It was essential to consider not only the participants' ability to make navigational decisions but also whether these decisions may be supported. For example, at a junction in an environment, wayfinding aids, such as maps, may be placed [42]. Therefore, we also considered aided wayfinding, which can assist with navigational decisions and may use signs and route instructions [43]. Furthermore, we identified that aided wayfinding could also consist of deterrents (e.g., no-way signs) (Fig 2). When considering wayfinding aids, we acknowledged that removing information or aids might hinder completing a task. For example, the visual removal of a straight path may impact an individual's ability to walk a straight path. Similarly, the environmental design might aid explorative tasks, such as architectural spaces and information points.

Therefore, this theme contained two categorical scales, including 'task-based instructions' (1-5 (Restrictive – Explorative)) and 'wayfinding aids' (A aided – E unaided).

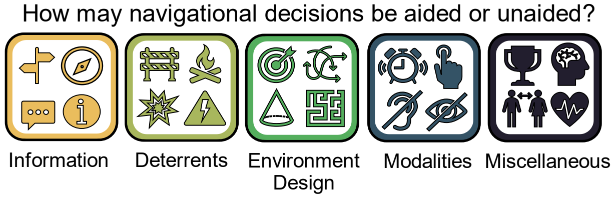

Fig. 2. Aided Wayfinding

2.2 Theme 2: Technique Implementation

The second theme considered technique implementation. Many reviews have provided in-depth information regarding fundamental principles of various redirection techniques, such as scripted controllers and change blindness, and how they can be implemented [4], [12]. Additionally, some articles define whether techniques use subtle manipulations (occur without the user's knowledge) or overt manipulations (detectable by a user) [9], [11] and if they are applied continuously or at discrete time intervals [9], [44].

Consequently, we created two subthemes regarding technique implementation to ensure a novel approach to the RDW literature. The first subtheme is built upon existing categories, such as continuous or discrete implementations [9], [44]; however, it regards guidance. In contrast to theme one and the use of the term 'instructions', we distinguished between instructions regarding the study task and guidance as to the underlying mechanisms of a technique in which we defined the terms positive and negative guidance as: ***positively** guided the users (e.g., guidance towards an area, assisting the task/goal) or **negatively** guided the users (e.g., guidance away from an area, hindering completing a task).*

Positive guidance may use a discrete approach, such as change blindness, in which the positions of virtual doors are changed [45], [46] without directly impacting the tracking of the user and allowing users to explore a larger VE. In contrast, negative guidance may introduce something that forces users to backtrack along a route and alter their navigational decisions, such as a warning sign.

However, gain-based techniques may be applied continuously, guiding the user away from one area and towards another simultaneously, using both positive and negative guidance. Additionally, in 1:1 mapping, users' movements are directly mapped from the real world to the VE [47], [48], neither using positive nor negative guidance. Therefore, guidance comprises of four categories: *'positive'*, *'negative'*, *'mismatch'*, and *'N/A'*.

The second subtheme in Technique Implementation considered whether locomotion techniques use subtle or overt manipulations [9], [11]. However, we did not consider technique fundamentals. Instead, we considered the implementation of locomotion techniques in conjunction with study methodologies. For example, in a study examining the noticeability of gain techniques, the technique could be investigated explicitly (shown clearly and openly without any attempt to hide anything, e.g. verbal acknowledgement of goal [49]), for example, in work by Engel et al. [50]: *"After the turn they were asked to report whether they turned more or less then 90 degrees in the* *real world"* – page 159, [50]. Alternatively, the technique could be investigated implicitly (something that is not communicated directly, e.g. contextual cueing [49]), for example, in work by Hodgson et al. [51]: *"At the end, RDW and the purpose of the study was explained."* – page 583, [51].

Whether a locomotion technique is investigated explicitly or implicitly, we acknowledge that information may or may not be attended to [52], [53]; hence, studies explore the noticeability of gain amounts. For example, participants may not be told they are using a gain technique but must still adapt to visual and vestibular mismatches. Therefore, noticeability consists of *'Implicit', 'Explicit', 'Implicit and Unconscious',* and *'Explicit and Unconscious*.*'* The phrase unconscious denotes a technique that includes manipulation or deception, whether investigated implicitly or explicitly. The purpose of creating these categories was not to indicate the results of a paper, such as technique noticeability, but to identify different study methodologies.

2.3 Theme 3: Modalities

For the third theme, we considered materials and modalities. A previous survey by Cardoso and Perrotta [8] mentioned visual, auditory and olfactory information. VR research and development indicate that audio-visual modalities are predominantly used [54].

Additionally, modalities can also include haptic and gustatory information [55]. Haptic feedback may use passive feedback where a physical object can be associated with a virtual item [4] or the integration of thermal feedback [54]. Fisher and colleagues [56] mention visceral interaction, which they relate to speech and gesture input technologies and tactile interaction via gloves and motion sensors [56], [57], which can be used to apply force or vibrations [58]. We can also use internal body information, such as vestibular and proprioceptive information [59].

Olfactory may be achieved using olfactory displays [55]; gustatory has technological constraints, so it may be limited to being mimicked through other senses [55]. Therefore, gustatory and olfactory modalities may be challenging to introduce in VR [55], so we do not expect many papers that include these modalities.

Additionally, cultural information is also presented alongside modalities. For example, path-following consists of visual information, but there is also a cultural association. For example, without a sign saying, *"please keep off the grass."* we may still see individuals gravitating to walk along the tarmac or a designated path even without explicit information [60]. This phenomenon may occur because of social constructs and prior knowledge. For example, to keep the grass healthy or the association that the grass may be muddy [60]; therefore, modalities and information encompass cultural elements.

In sum, there are five categories in the theme of modalities: visual (any visual element), auditory (e.g., white noise), haptic (passive haptic), other (olfactory, taste, somatosensory), and cultural. We did not include task-specific instructions under modalities. Additionally, the cultural modality was not analysed, as this is a substantial additional piece of work outside this analysis's scope. However, each experimental condition acknowledged the cultural modality.

3 METHODOLOGY

The LoCoMoTe framework aims to provide ongoing order and structure to the VR locomotion literature. By categorising the differences in experimental procedures and materials to help best understand human navigation and behaviour in VR and encourage open science and data-sharing. Therefore, to develop the LoCoMoTe framework, the aim was not to critique the existing literature but to analyse the methodologies used in experiments. Thus, no quality assessment of the papers is included in this work.

3.1 Process

To refine the themes of the LoCoMoTe Framework, we began by defining our inclusion criteria:

1. Written in the English language.
2. Published in journals or conferences.
3. Live-User Studies.

Google Scholar was initially used to identify five detailed review papers within VR locomotion based on the authors of the work, place, and date of publication [6], [8], [9], [10], [11], which referenced 479 papers between them. Next, a backwards snowballing approach was adopted [61]. Figure 3 details the initial identification and retrieval

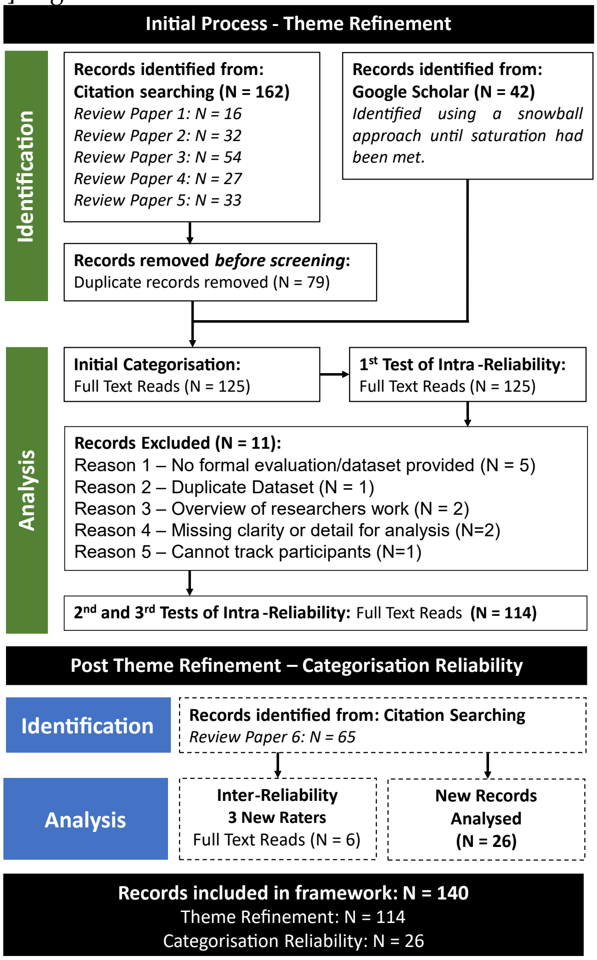

Fig. 3. The overall process (review papers: [6], [8], [9], [10], [11], [14])

of papers from the reference searching of the five detailed review papers that met our inclusion criteria (*N = 162 papers)* and the removal of duplicates (*N = 79 papers*). To ensure that the development of the LoCoMoTe themes was not limited to the initial papers (*N = 83 papers*), we also used a forward snowball approach to cover various subject areas and techniques that may employ different tasks.

We used google scholar to identify citations of previous papers [61] and keywords including education, learning, multi-user, affordances, and eye-gaze alongside virtual reality (*N = 42 papers*). Additionally, during intra-reliability checks, additional papers were removed for various reasons, such as duplicate data (*N = 11 papers, Fig. 3*). Therefore, the final corpus used to refine the themes was N = 114. We then analysed additional papers (*N = 26*) to assess the theme refinement for reliability. Therefore, the final corpus included in this analysis was N = 140 papers.

3.1.1 Theme Refinement Process

The initial analysis of each paper contained one full-text read, identifying experimental conditions, with each theme analysed sequentially (Fig. 3). We kept quotes from papers corresponding to the LoCoMoTe framework categorisation in a supporting document. When analysing and categorising the papers, many contained descriptions of multiple studies and techniques; therefore, it was sometimes appropriate to separate aspects of an experiment into different parts.

We categorised 682 experimental conditions identified from the 114 papers during the theme refinement, corresponding to each theme. Each experimental categorisation was kept in spreadsheets. However, if there were no changes between the three themes, we did not include a detailed breakdown of techniques in the spreadsheets. For example, in the work by Kruse et al. [62], different translation gain amounts were tested in three conditions. Although we distinguished between the three study conditions, we grouped the translational gain amounts, except for the gain of 1 (1:1 mapping) [62].

To ensure rigor, we considered credibility, transferability, dependability, and conformability [38], [63]. Credibility may be achieved through triangulation [38]. Investigator triangulation is one approach that considers multiple investigators to examine and analyse the same data [63] to minimise bias from an individual researcher [64]. During the theme refinement process, coding was conducted by a single researcher. However, the themes and results were discussed with co-authors throughout the analysis.

Furthermore, credibility may also be established using prolonged engagement and persistent observation [38]. Consequently, intra-reliability checks were completed once saturation was met to strengthen researcher dependability, including reanalysing the academic papers [65]. We considered saturation was met when additional data did not impact any theme [66] regarding the consistency of each theme category during analysis [67].

A series of tasks were included during intra-reliability (Fig. 3). The first task was to re-read the full text as if reading the papers for the first time, identifying any changes (identification, removal, or re-categorisation of experimental conditions) that may occur, and updating both the quotes and table documents accordingly. On average (across each theme), experimental conditions remained the same during intra-reliability for check 1 = 46.81%, check 2 = 86.48%, and check 3 = 80.44% (see supplementary material for a more detailed breakdown). At the same time, it was essential to identify results by checking paper publications for the same authors, the same task implementations, and the same demographics. If all three were identified, only one paper would be included (often the paper with more detail). Once these steps were completed, all experimental categorisations were compared to ensure continuity. Initially, this was completed by recording each paper's quotes and placing them into a separate document corresponding to specific categories. However, by the 3rd intra-reliability check, this process had changed to writing the summaries of each category with all examples, allowing for easier identification of incorrectly placed categorisations. For each intra-reliability check, we kept a separate spreadsheet showing changes to each paper's categorisation. The Intra-reliability checks conducted during the theme refinement process were paramount in developing the LoCoMoTe framework, as they highlighted categorical errors, e.g., Experimental conditions previously missed.

Between the first complete categorisation to the 1st completed test of intra-reliability, there were 30 working days. Between the 1st and 2nd complete checks of intra-reliability, there were 75 working days. Between the 2nd and 3rd completed checks of intra-reliability, there were 16 working days. Most papers analysed during theme refinement were last accessed on the 19th of July, 2021.

3.1.2 Categorisation Reliability Process

After the theme refinement process, which included the analysis of 114 papers, we used this opportunity to assess the reliability of the LoCoMoTe themes and categories with the analysis of new papers. Therefore, the LoCoMoTe framework was updated by conducting another backward snowball approach on a review paper from 2022 [14]. This review paper referenced 124 papers. These papers were then refined to those not already analysed (*N = 65*). Following this, N = 26 papers met our inclusion criteria, were not duplicates, and were thus included in the final analysis. Similar to the theme refinement process, each paper contained an initial full-text read, with each theme analysed sequentially. We categorised 295 experimental conditions identified from the 26 papers during the categorisation reliability process. These new 26 papers were accessed between the 14th of February, 2023, to the 10th of March, 2023. Therefore, with both the papers analysed during theme refinement and the categorisation reliability, the final corpus analysed at publication was N = 140 papers (Fig 3).

Since an individual researcher conducted the theme refinement process, we conducted inter-coder reliability tests to ensure the categories were robust. We used the theme refinements analysis to create a guide on each theme, and its associated categories, with examples (see

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supplementary material). The guide was then given to three new coders who were all familiar with VR but not specifically the topic of locomotion in VR. Each coder received a copy of the guide, a blank structured document, and links to six random papers [68], [69], [70], [71], [72], [73] identified from the backwards process on the review paper from 2022 [14]. Each coder was tasked with analysing the six papers corresponding to each theme in the LoCoMoTe framework: Navigational Decisions, Task Implementation and Modalities.

Provided that the entire paper and no specific textual or image extractions were given to coders, there were instances of missing experimental condition categories because not every coder had identified the same experimental aspects, e.g., 1:1 Mapping. Therefore, to assess inter-coder reliability, we used Krippendorff's alpha with nominal metric differences [74], [75], in which we considered values above $_c\alpha = 0.8$ to be a good indicator of reliability and values between $_c\alpha = 0.67$ and $_c\alpha = 0.80$ acceptable for tentative reliability [76].

Using a Krippendorff's alpha with all four coders (including the researcher who analysed the previous papers during the theme refinement process), for theme 1: navigational decisions, there were 46 comparable responses, resulting in $_c\alpha_{\text{nominal}} = 0.72$, suggesting tentative reliability. For theme 2: technique implementation, there were 30 comparable responses, resulting in $_c\alpha_{\text{nominal}} = 0.49$. A lower reliability agreement for technique implementation was likely a limitation of coders not being familiar with locomotion techniques and the underlying mechanisms regarding manipulation, making it challenging to categorise. For theme 3, modalities, there were 92 comparable responses, resulting in $_c\alpha_{\text{nominal}} = 0.69$, suggesting tentative reliability. Although there were differences between the expert on the framework and the additional three coders, we believe it is likely that with more training and familiarity with experimental work, the themes refined for the LoCoMoTe framework should hold.

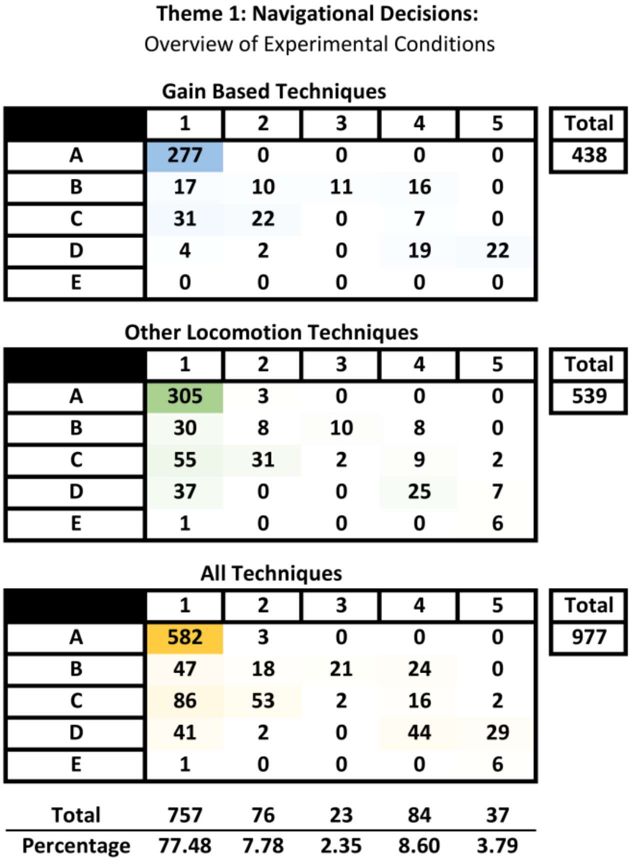
4 ANALYSIS AND REFINEMENT OF THEMES

The LoCoMoTe framework aims to provide ongoing order and structure to the VR locomotion literature. By categorising the differences in experimental procedures and materials, the framework supports an improved understanding of human navigation and behaviour in VR and encourages open science and data-sharing. The LoCoMoTe framework categorises three themes concerning study methodologies. Initially, theme refinement was developed from the analysis of 114 academic papers. The refined themes were then assessed regarding reliability by analysing 26 new papers. Below we discuss the papers analysed at the time of publication and the development of each theme regarding codes produced inductively and observations based on the framework. We have not included the full analysis details from each paper for ease of reading. Therefore, the details (quotes, categorisations of experimental conditions (977) and reliability checks) of every paper can be found in the supplementary material.

4.1 Theme 1: Navigational Decisions

The theme of navigational decisions regards descriptions of 'task-based instructions' along a categorical scale of 1-5 (Restrictive – Explorative) and 'wayfinding aids' along a categorical scale of (A aided – E unaided) highlighted in the methodologies of published papers. To recap, initial expectations of the categories were: '1' tasks that do not allow participants to make navigational decisions, e.g., path following, '3' represented task-based scenarios, and '5' represented explorative tasks.

During the theme refinement process and the analysis of the 114 papers for developing the LoCoMoTe framework, we achieved saturation during the code development of this theme. During the theme refinement analysis, 70.5% of experimental task-based instructions were identified as not allowing participants to make navigational decisions and were thus categorised as 1X (where X represents wayfinding aids on a categorical scale of A *aided* – E *unaided*).



Theme 1: Navigational Decisions:
Overview of Experimental Conditions

Gain Based Techniques

	1	2	3	4	5	Total
A	277	0	0	0	0	438
B	17	10	11	16	0	
C	31	22	0	7	0	
D	4	2	0	19	22	
E	0	0	0	0	0	

Other Locomotion Techniques

	1	2	3	4	5	Total
A	305	3	0	0	0	539
B	30	8	10	8	0	
C	55	31	2	9	2	
D	37	0	0	25	7	
E	1	0	0	0	6	

All Techniques

	1	2	3	4	5	Total
A	582	3	0	0	0	977
B	47	18	21	24	0	
C	86	53	2	16	2	
D	41	2	0	44	29	
E	1	0	0	0	6	
Total	757	76	23	84	37	
Percentage	77.48	7.78	2.35	8.60	3.79	

Fig. 4. Categorisation of all experimental conditions identified from the 140 papers: [9, 15, 16, 21, 28, 41, 45, 47, 50, 51, 59, 62, 68 - 73, 77 - 197]

When analysing the 26 papers for categorisation reliability, this increased from 70.5% to 77.5% (Fig. 4) of experimental task-based instructions that were identified as not allowing participants to make navigational decisions. Furthermore, the 26 papers analysed during the categorisation reliability did not impact the categories developed through the theme refinement process (Fig 5). Before the theme refinement process, we initially identified

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Theme 1: Navigational Decisions

		Restrictive				**Explorative**
		1	2	3	4	5

Aided	A	• **Path and/or target following:**
		  • Following avatars or directed mazes
		• Passing through apertures
		• Rotations in set directions
			• **Walking from one side of a room to another**
			  • Only a small veering around another person required.			

	B	• Walking backwards along a path
		• Transparency applied to waypoints
		• Walking to targets without visual information
			• **Path and/or target following:**
			  • Priming paths
			  • Gamification
			  • Visible real world
				• **Searching for objects in small VEs**
				  • Collecting distinctive object in a small VE
				• **Gamification**
				  • Destroying an enemy boss in a VE with 1 route and attacking multiple enemies that appear.
					• **Identification and collection of target objects with:**
					  • Gamification
					  • Remembering unique landmarks
					  • Use of signs
					  • Small search area	

	C	• **Spatial awareness tests**
		  • Walking or turning towards a previously seen target
			• **Path and/or target following but with:**
			  • Navigation around objects
			  • Choice of different routes
				• Perception task in a small VE	• **Collection of visible items in a small VE**
					  • But with no specific collection order
					• **Exploring an art gallery**
					  • But having to study each piece in detail
					• **Training task**
					  • Had to move to objects in a small room
						• **Explore a restricted layout VE**
						  • Exploration of an aeroplane for a set time

	D	• **Spatial awareness tests**
		  • Walking or turning towards a previously seen target without any visual information
			• **Path and/or target following but with:**
			  • Navigation around objects but with only audio information (*no visual information*)
					• **Finding target locations with no navigational aids**
					  • e.g., signs or arrows
						• **Exploration but with:**
						  • stopping if participants saw a stop sign
						  • Architectural spaces, including corridors and linear flowing rooms
						  • Outside VEs with some path formations
						  • Inclusion of avatars
						• **Training task**
						  • Moving and picking up objects

Unaided	E	• Asked to imagine walking along a straight path				• **Familiarity and training sessions** • Real-world room replications with minimal to no virtual objects

Fig. 5. Overview of experimental categorisations based on tasks-based instructions and wayfinding aids. Greater detail can be found in the supplementary material.

some codes for code development, including '*path*', '*target*', '*following*', '*choice*', '*exploration*', and '*task*'. However, we acknowledged that too many predefined codes might complicate analysis [38]. Therefore the creation of additional codes using only a deductive approach [67] was not applicable. Consequently, to account for semantics, we also used an inductive coding approach considering phrases that may or may not mean the same thing [67] to aid categorisation.

For both the theme refinement and categorisation reliability analysis, many task-based instructions were easy to identify and categorise on the categorical scale of 1-5 (Restrictive – Explorative) from text alone.

For example, following paths or targets [40], [154] or paths with junctions [143], [177], [179]. However, semantics did complicate the analysis as anticipated. Instances of the phrase '*freely*' sometimes referred to the participants being technologically free from wires rather than an explorative task [127]. Additionally, issues regarded the lack of detail or clarity of study methods. For example, one paper mentioned that participants were required to walk around a block, which is ambiguous. However, when looking at the supporting figures, the placement of the block in the VE verified that the categorisation would be 1A, as it formed a linear path [50]. Therefore, in many cases, content analysis was applied to accompanying figures.

Furthermore, attention was needed to identify priming in experiments. For example, one experiment did not appear to override initial explicit instructions on following a virtual agent [133]. Consequently, the entire study was recategorised as 'a following' task and changed from 3A to 1A.

The process of theme refinement, including code development, intra-reliability, and paper analysis, highlighted the differences along the wayfinding aid categorical scale (A aided – E unaided) (Fig 5). Our approach to categorising the differences on this scale focused on removing the visual modality as one reason for decreasing the wayfinding aid categorical scale (A aided – E unaided). For example, path-following tasks with spatial awareness tests, e.g., removal of the visual modality; thus, participants would have to rely only on working memory to either walk towards or indicate the direction of a target location [112], and were often categorised as 1D.

Overall, categorisations on the wayfinding aid categorical scale (A aided – E unaided) may differ depending on the participant demographics. For example, we may expect veering to occur when trying to walk a straight path without reliable orientation-based cues, e.g., visual cues [198], [199] for participants with and without visual impairments [198]. However, training to reduce veering has worked for blind and blindfolded participants [198]. Therefore, we cross-referenced papers to indicate non-corrected visual impairments or hard-of-hearing participants and found nothing that would concern our initial categorisations. However, future research questions, training and demographics may impact these categorisations.

Overall, we found it particularly useful to consider the figures and the text simultaneously, as this impacted the final categories.

4.2 Theme 2: Technique Implementation

The theme of technique implementation consisted of guidance and noticeability. Guidance was inspired by the existing categories of continuous or discrete implementations [9], [44], which we used to develop four categories: *'positive'*, *'negative'*, *'mismatch'*, and *'N/A'*. As anticipated, during the theme refinement process, the guidance of technique implementations was easy to categorise because the fundamentals of techniques themselves do not change. Thus, the guidance subtheme was identified as redundant, as it implied which technique was used. It was decided that the subtheme of guidance would be removed from the LoCoMoTe framework, and the technique would be referred to by itself. Therefore, for the categorisation reliability process, guidance was not analysed.

For the second subtheme, 'noticeability', we did not categorise the fundamental design of a technique regarding subtle or overt manipulations [9], [11]. However, as discussed in section 2.2, we did need to acknowledge techniques that contain manipulation and the implementation of techniques within study methodologies. Consequently, we devised four categories: '*Implicit*', '*Explicit*', '*Implicit and Unconscious*', and '*Explicit and Unconscious*'.

During the theme refinement and categorisation reliability analysis, we did not identify any implicit only techniques. However, we did identify many explicit only techniques. These techniques require explicit instructions to use the locomotion technique, for example, 1:1 mapping.

However, we acknowledged that participants may not have attended to the underlying manipulation of some techniques, such as rotational gains. Therefore, depending on the study methodology, some techniques could be categorised as *'implicit and unconscious'* or *'explicit and unconscious'* (Fig 6). For example, studies may ask two-alternative forced-choice (2AFC) questions, such as whether participants thought they turned more or less than 90° [50], [87] at the end of each trial. It is essential to pay attention to the wording of these questions, as some may not consider the technique but another element of the VE. For example, instead of being asked about perceived distance with translational gains, participants were asked about perceived slope steepness [151].

Additionally, careful attention was required to identify instances of priming. Some technique implementations could have been categorised as '*implicit and unconscious*' but introduced priming. For example, multiple studies encouraged participants to indicate if something *"feels strange or unnatural"* – page 1626, [41]. Sometimes focus was placed on possible issues with the motion capture system [41], implausibility [148], or when they think there is a bug in the software [140]. We counted priming as explicit and unconscious rather than implicit and unconscious because these approaches may lead to potential biases within the data and may occur without being consciously aware [200].

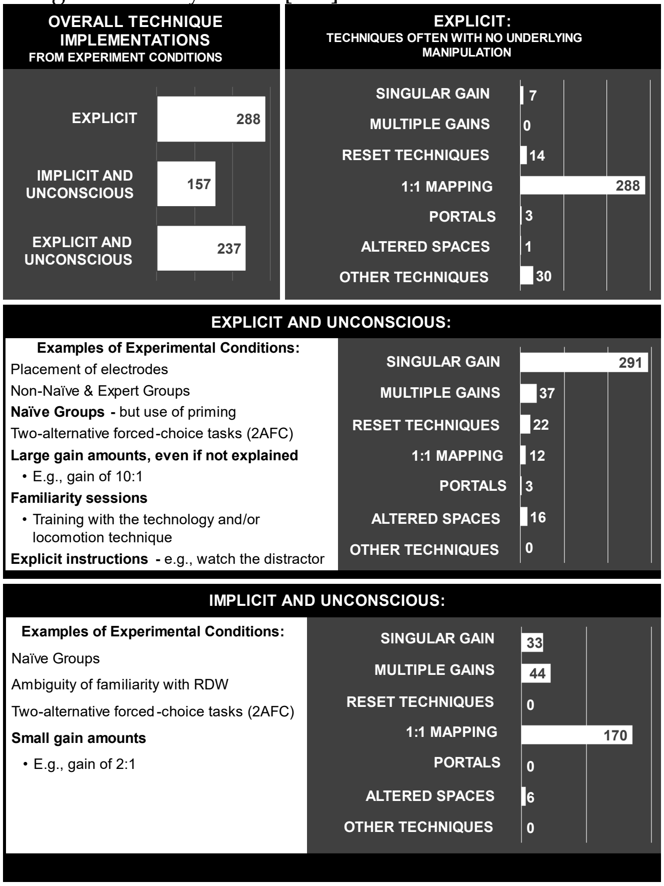


Fig. 6. Short overview of technique implementations regarding noticeability: the total is 977 (experimental conditions). Altered spaces refer to techniques such as flexible spaces, and other techniques refer to techniques such as the magic barrier tape method. Greater detail can be found in the supplementary material.

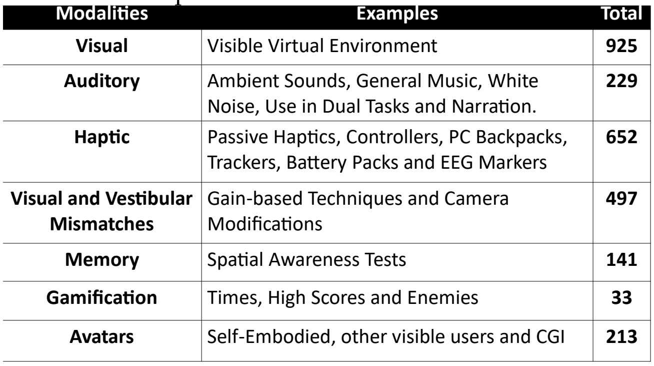
4.3 Theme 3: Modalities Used

The final theme categorised modalities. We acknowledge that all locomotion techniques and task implementations encompass cultural information. However, we did not analyse this within the framework development because behaviour can depend on different factors, such as personality and general demographics [201]. Not all of these will be available in detail in research papers to perform ethnographic research; thus, we did not explore this research avenue.

As expected, the visual modality was often provided through a VE (Fig. 7). Although occasionally, the VE was absent [119], [149] or was never included [87], [89]. Particular attention must be paid to removing visual elements of VEs, commonly used for spatial awareness tests [115], [168] or audio-only groups [93], [127].

Furthermore, we carefully considered phrases such as *"participants wore headphones"* as there was ambiguity as to whether any audio was played [83], [140] and thus were not included in the categorisation. Additionally, sometimes audio was not specified but mentioned [113], [141], [145] and therefore included in the categorisation.

We initially considered the haptic category concerning specialised devices, such as haptic shoes [118], [119]. However, during the theme refinement analysis, the need emerged to categorise additional equipment (Fig. 7), such as participants holding controllers, even if they were not used directly for the technique. For example, to interact with elements in the VE, such as buttons and selecting targets [78], [79]. Including these additional study elements allow researchers to differentiate between different study methodologies, no matter how small, which could impact human behaviour in VR.



Modalities	Examples	Total
Visual	Visible Virtual Environment	**925**
Auditory	Ambient Sounds, General Music, White Noise, Use in Dual Tasks and Narration.	**229**
Haptic	Passive Haptics, Controllers, PC Backpacks, Trackers, Battery Packs and EEG Markers	**652**
Visual and Vestibular Mismatches	Gain-based Techniques and Camera Modifications	**497**
Memory	Spatial Awareness Tests	**141**
Gamification	Times, High Scores and Enemies	**33**
Avatars	Self-Embodied, other visible users and CGI	**213**

Fig. 7. Short overview of Modalities for each experiment. The total is 977 (experimental conditions). Greater detail can be found in the supplementary material.

Similar to the haptic categorisations, we initially anticipated the 'other' modality to consist mainly of visual and vestibular mismatches. However, during the theme refinement process, we noted experimental conditions considered the use of memory, gamification, and avatars. Sometimes avatars were embodied by real-world people [92], [126], although it was not always clear if they responded or were visible to participants [15], [102].

5 DISCUSSION

The current work reported in this paper developed the LoCoMoTe framework to facilitate the ongoing structuring and comparison of the VR locomotion literature. This was achieved by categorising the differences in experimental procedures and materials to help best understand human navigation and behaviour in VR in different contexts and encourage open science and data-sharing. The LoCoMoTe framework has three themes: navigational decisions, technique implementation, and modalities. It was developed by categorising 977 experimental conditions identified from 140 papers.

The first theme, navigational decisions, considered the task-based instructions given to participants and the opportunities to make navigational decisions. All experimental conditions were mapped along two categorical scales, including task-based instructions (1-5 (restricted to explorative)) and wayfinding aids (A aided – E unaided) (Fig. 5). We identified the main themes between the task-based instructions as:

1. Path or target following.
2. Navigate around an obstacle or choice between a few well-formed paths to identifiable target locations.
3. Task-based instructions that had small VEs, sometimes without well-formed paths.
4. Explorative search tasks or learning-based tasks.
5. Purely explorative tasks are often used in familiarisation or transitional VEs.

These distinctions give researchers an overview of the research landscape and identify trends and results pertinent to their research questions. For example, researchers are looking to understand how best to replicate human navigation behavior in VR when there are dynamic objects [20] and multiple target objects [19]. In this case, category '4' may be appropriate as it identifies tasks that regard finding target objects (Fig. 5). However, whilst we distinguished between categories, we acknowledge that these categorisations may overlap. Exploring results from different categorisations may be appropriate depending on the research question. For example, research regarding path-following could explore the use of obstacles where it may be appropriate to consider experiments from categories '1' and '2'.

Additionally, it may be appropriate to distinguish between experiments within these categories. We have made some distinctions using the wayfinding aid (A aided – E unaided) categorical scale, including removing the visual modality for spatial awareness assessments. Provided research has highlighted the sensitivity of RDW algorithms to the nuances of walking [24], similar tasks with varying levels of information given to participants could be compared. For example, path-following tasks categorised as '1A' provide a clearly defined path. However, at the other end, category '1E' contained an experimental condition that required participants to imagine walking along a straight path with no feedback [119]. These distinctions could identify similarities and differences in human walking behaviour in VR with varying information, including stumbling and veering.

The second theme, 'technique implementation', initially consisted of two subthemes: guidance and noticeability. The subtheme of guidance was identified as redundant during the theme refinement process, as it implied which technique was used and therefore was removed. For the subtheme of noticeability, we considered whether techniques were made known to participants during the user studies (Explicit or Implicit). Therefore, careful consideration was applied to research methods such as between groups, familiarisations, and questionnaires.

Furthermore, we often categorised priming in studies as explicit and unconscious, as this may lead to potential biases within the data and may occur without information being attended to [200]. Consequently, the phrase *unconscious* is used to represent a technique with manipulation but not to denote the noticeability of a technique. Using the technique implementation theme allows researchers to compare the impact of various experimental methods, including 2AFC tasks, familiarisation sessions, and priming of participants on locomotion techniques.

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For the last theme modalities, we considered the equipment and other information. Although we acknowledged cultural information for every experiment, we did not analyse this. Furthermore, we did not identify any uses of olfactory and gustatory modalities from the selection in the current literature. However, these may be introduced along with new technological equipment. The most diverse category was 'other', for example, visual and vestibular mismatches, avatars, and gamification. In future iterations of this framework, it may be appropriate for each category to be broken down further.

Whilst these themes can be used individually, they can also support one another to identify similarities and differences between experimental conditions and results. For example, research questions may explore the effects of self-embodied and computer-generated avatars on navigational decisions across the task-based instructions categorical scale of 1-5 (restricted - explorative).

A crucial point of developing the LoCoMoTe framework was that it was not intended as complete work or a complete literature representation. Instead, the VR research community should continually expand and refine this work. By categorising different papers and experiments, researchers can oversee the research field and highlight possible training data and trends. For example, at the time of publication, the papers analysed during the development of this framework indicate that 77.5% of experimental conditions were categorised as following-based tasks (e.g., following a non-branching path) and allowed for no navigational decisions, highlighting a need for more varied tasks. With the expansion of this framework, the wayfinding aids categorical scale (A aided – E unaided) is the area that may see the most change, with additional papers introducing different aspects, such as gamification, multi-user scenarios, and different population demographics.

Overall, we anticipate the categorical distinctions in the LoCoMoTe framework, developed by identifying different experimental methods identified from the analysed papers, should support the reproducibility and replicability of RDW experiments [31], [202]. Furthermore, this study did not attempt to access the datasets of each paper analysed. Our goal was to present a standardised framework for comparing the literature. Therefore, we hope the LoCoMoTe framework encourages data sharing where appropriate. However, we acknowledge that even if researchers share live-user data containing user paths, not all of these paths will be suitable for input during simulations and may not fully model users' reactions to RDW [24]. Hirt and colleagues [24] highlight important questions such as: *"how such unclean behavior can be modeled more or less realistically in simulation, for example by inducing random perturbations during resets?"* – page 531 [24]. While the LoCoMoTe framework cannot answer these questions alone, as there is no extraction or quality assessment of datasets, it does provide a systematic way to analyse paper methodologies. Thus, the LoCoMoTe framework provides a foundation to work from and answer these questions.

5.1 Limitations

To develop the LoCoMoTe framework, we extensively analysed relevant papers until saturation had been achieved (140 papers), and from them, categorised 977 experimental conditions. We acknowledge that although the work presented in this paper is an extensive analysis of the literature, it is not a complete representation of all the literature in the field. The LoCoMoTe framework is designed to be an ongoing and dynamic resource that should be community driven and updated accordingly. Furthermore, it can be challenging to minimise subjectivity during analysis [203]. Assumptions always have to be made; arguably, some of these categorisations may be inaccurate [203]. However, we took steps to reduce researcher bias by conducting three intra-reliability checks. We wanted to focus carefully on the papers to minimise subjectivity [203]. Therefore, we kept additional documents alongside the categorisation of experimental conditions referring to direct quotes from the papers (supplementary material), ensuring that we considered validity by keeping a thorough document [203].

Furthermore, we conducted inter-coder reliability. There was tentative reliability for theme 1: navigational decisions and theme 3: modalities. Although there were differences between the expert on the framework and the additional three coders, we believe these differences were likely a limitation of the additional coder's unfamiliarity with locomotion techniques, having limited training (only received a guide), and categorising work that they were unfamiliar with, leading to assumptions having to be made. Therefore, we believe it is likely that with more training on the LoCoMoTe framework and familiarity with the experimental work presented in the papers, the themes refined for the LoCoMoTe framework should hold. Therefore, it is recommended that those familiar with the research studies should enter the coding of experimental conditions into the LoCoMoTe framework.

Finally, we have not currently performed a formal evaluation of the framework at the time of publication. The LoCoMoTe framework aims to provide ongoing structure to the VR locomotion literature, including identifying similarities and differences in experimental methodologies that may produce context-dependent results, thus supporting future RDW research with either live users or simulation-based experiments. Therefore, we expect a formal validation to occur on a longitudinal basis (1+ year) on the topics of: *"Do researchers use this framework to categorise their work? If so, do the categorical distinctions made in the LoCoMoTe framework help identify gaps, and are researchers working towards addressing these gaps?"* and *"Do the categorical distinctions in the LoCoMoTe framework help identify pre-existing user path data from different contexts to train intelligent agents in simulation-based experiments? If so, are researchers sharing research data where appropriate, and how has this affected the RDW research field?"*

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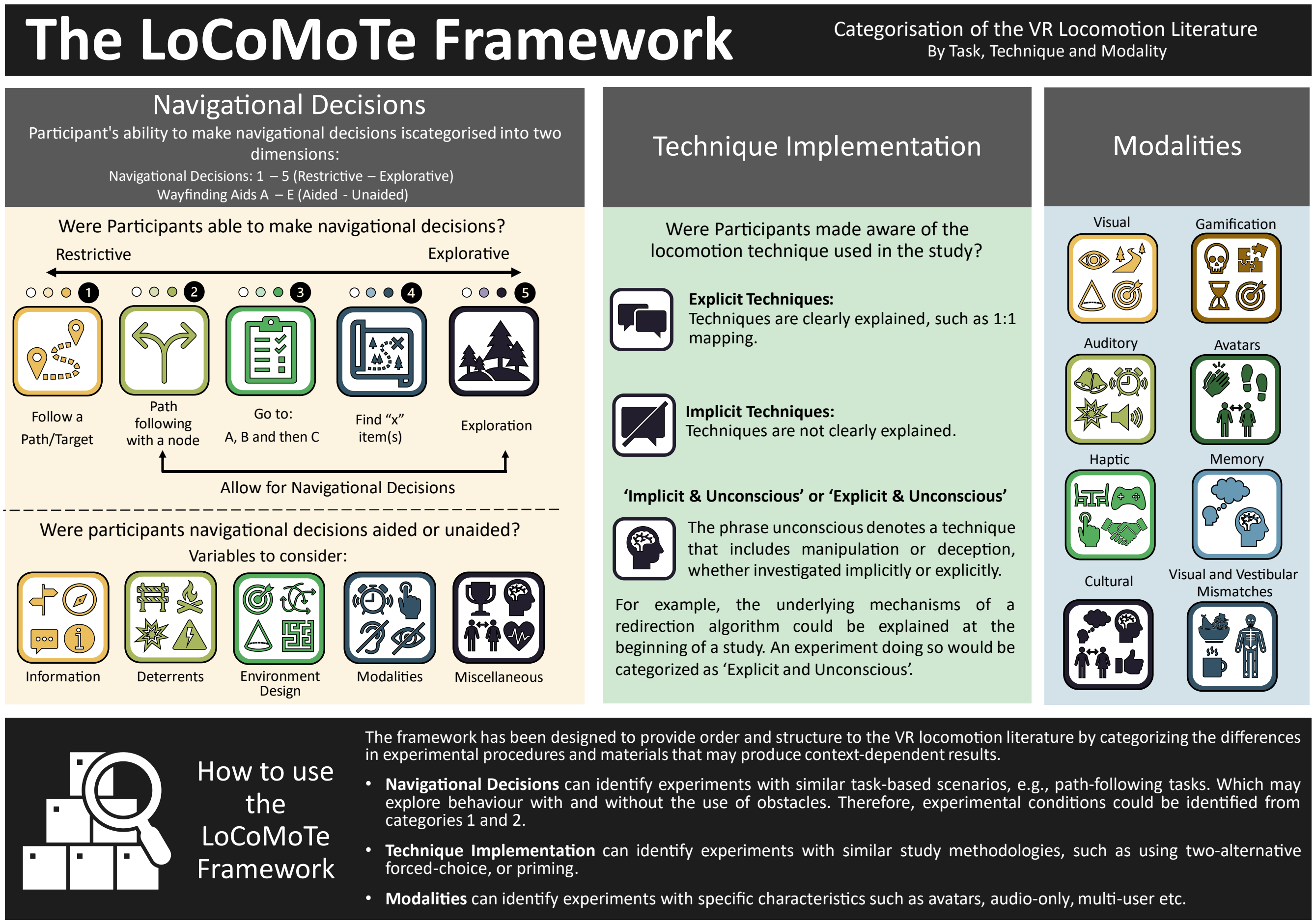

Participant's ability to make navigational decisions iscategorised into two dimensions:

Navigational Decisions: 1 – 5 (Restrictive – Explorative)

Wayfinding Aids A – E (Aided - Unaided)

Were Participants able to make navigational decisions?

Were participants navigational decisions aided or unaided?

Variables to consider:

Were Participants made aware of the locomotion technique used in the study?

Explicit Techniques: Techniques are clearly explained, such as 1:1 mapping.

Implicit Techniques: Techniques are not clearly explained.

'Implicit & Unconscious' or 'Explicit & Unconscious'

The phrase unconscious denotes a technique that includes manipulation or deception, whether investigated implicitly or explicitly.

For example, the underlying mechanisms of a redirection algorithm could be explained at the beginning of a study. An experiment doing so would be categorized as 'Explicit and Unconscious'.

The framework has been designed to provide order and structure to the VR locomotion literature by categorizing the differences in experimental procedures and materials that may produce context-dependent results.

- **Navigational Decisions** can identify experiments with similar task-based scenarios, e.g., path-following tasks. Which may explore behaviour with and without the use of obstacles. Therefore, experimental conditions could be identified from categories 1 and 2.
- **Technique Implementation** can identify experiments with similar study methodologies, such as using two-alternative forced-choice, or priming.
- **Modalities** can identify experiments with specific characteristics such as avatars, audio-only, multi-user etc.

Fig. 8. Summary of the LoCoMoTe Framework

6 CONCLUSION

Research has begun to explore the development of RDW algorithms using RL [16], [18]. To support this work, we must understand how best to replicate human navigation and behaviour in VR [20], which can be supported by accumulating results produced through live-user experiments [25]. However, building upon relevant research in an ever-changing field is challenging [23]. Therefore, to provide an ongoing structure to the VR locomotion literature, we developed the LoCoMoTe framework (Fig. 8). Using thematic analysis, we considered three themes: 1) navigational decisions, 2) technique implementation, and 3) modalities.

The current work analysed 140 academic papers identifying and categorising 977 experimental conditions. Of these, we analysed 114 papers to refine our initial conceptual themes. Then an additional 26 papers were used to assess the categorisation reliability. These 977 experimental conditions were identified from 140 academic papers because of the use of a) multiple experiments presented in papers, b) the breakdown of tasks in experiments to include elements such as transitional environments, and c) study conditions, e.g., multi-user, naïve groups. Elements such as the specifics of the breakdown of tasks may not be easily identifiable from the results. Additionally, it may be more appropriate to break down the categories further depending on the research questions. For example, we often grouped gain-based techniques despite different gain amounts if other variables remained the same. As such, the LoCoMoTe framework should be continually updated.

In this paper, we present the development of the LoCoMoTe framework. The primary contribution of this work is to provide ongoing structure and comparison of methodologies giving rise to human movement behaviour in VR. To help categorise research, identify gaps and train intelligent agents. Detailed analysis and categorisation of the papers used to develop this framework can be found in our supplementary material. Current work is developing an online application based on this framework. Once complete, researchers will be able to search among the themes, see similar approaches, and suggest new papers for categorisation. Furthermore, future research should explore the validation of this framework and its impact on the RDW research community.

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REFERENCES

[1] K. Vasylevska and H. Kaufmann, "Compressing VR: Fitting Large Virtual Environments within Limited Physical Space," *IEEE Computer Graphics and Applications,* vol. 37, no. 5, pp. 85-91, 2017, doi: 10.1109/MCG.2017.3621226.

[2] J. Lee, S. C. Ahn, and J.-I. Hwang, "A walking-in-place method for virtual reality using position and orientation tracking," *Sensors,* vol. 18, no. 9, p. 2832, 2018, doi: 10.3390/s18092832.

[3] M. Slater and M. Usoh, "Body centred interaction in immersive virtual environments," *Artificial life and virtual reality,* vol. 1, no. 1994, pp. 125-148, 1994.

[4] F. Steinicke, G. Bruder, L. Kohli, J. Jerald, and K. Hinrichs, "Taxonomy and Implementation of Redirection Techniques for Ubiquitous Passive Haptic Feedback," in *2008 International Conference on Cyberworlds*, Hanzhou, China, 22-24 Sept. 2008, pp. 217-223; doi: 10.1109/CW.2008.53.

[5] C. Boletsis, "The New Era of Virtual Reality Locomotion: A Systematic Literature Review of Techniques and a Proposed Typology," *Multimodal Technologies and Interaction,* vol. 1, no. 4, 2017, doi: 10.3390/mti1040024.

[6] N. C. Nilsson, S. Serafin, F. Steinicke, and R. Nordahl, "Natural walking in virtual reality: A review," *Computers in Entertainment (CIE),* vol. 16, no. 2, pp. 1-22, 2018, doi: 10.1145/3180658.

[7] G. Bruder, P. Lubas, and F. Steinicke, "Cognitive Resource Demands of Redirected Walking," *IEEE Transactions on Visualization and Computer Graphics,* vol. 21, no. 4, pp. 539-544, 2015, doi: 10.1109/TVCG.2015.2391864.

[8] J. C. S. Cardoso and A. Perrotta, "A survey of real locomotion techniques for immersive virtual reality applications on head-mounted displays," *Computers & Graphics,* vol. 85, pp. 55-73, 2019, doi: 10.1016/j.cag.2019.09.005.

[9] E. A. Suma, G. Bruder, F. Steinicke, D. M. Krum, and M. Bolas, "A taxonomy for deploying redirection techniques in immersive virtual environments," in *2012 IEEE Virtual Reality Workshops (VRW)*, Costa Mesa, CA, USA, 4-8 March 2012: IEEE, pp. 43-46; doi: 10.1109/VR.2012.6180877.

[10] M. A. Zayer, P. MacNeilage, and E. Folmer, "Virtual Locomotion: A Survey," *IEEE Transactions on Visualization and Computer Graphics,* vol. 26, no. 6, pp. 2315-2334, 2020, doi: 10.1109/TVCG.2018.2887379.

[11] N. C. Nilsson *et al.*, "15 Years of Research on Redirected Walking in Immersive Virtual Environments," *IEEE Computer Graphics and Applications,* vol. 38, no. 2, pp. 44-56, 2018, doi: 10.1109/MCG.2018.111125628.

[12] M. Di Luca, H. Seifi, S. Egan, and M. Gonzalez-Franco, "Locomotion Vault: the Extra Mile in Analyzing VR Locomotion Techniques," in *CHI Conference on Human Factors in Computing Systems*, Yokohama, Japan, 2021: ACM; doi: 10.1145/3411764.3445319.

[13] R. R. Strauss, R. Ramanujan, A. Becker, and T. C. Peck, "A Steering Algorithm for Redirected Walking Using Reinforcement Learning," *IEEE Transactions on Visualization and Computer Graphics,* vol. 26, no. 5, pp. 1955-1963, 2020, doi: 10.1109/TVCG.2020.2973060.

[14] Y.-J. Li, F. Steinicke, and M. Wang, "A Comprehensive Review of Redirected Walking Techniques: Taxonomy, Methods, and Future Directions," *Journal of Computer Science and Technology,* vol. 37, no. 3, pp. 561-583, 2022, doi: 10.1007/s11390-022-2266-7.

[15] D. Lee, Y. Cho, D. Min, and I. Lee, "Optimal Planning for Redirected Walking Based on Reinforcement Learning in Multi-user Environment with Irregularly Shaped Physical Space," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Atlanta, GA, USA, 22-26 March 2020: IEEE, pp. 155-163; doi: 10.1109/VR46266.2020.00034.

[16] W. Shibayama and S. Shirakawa, "Reinforcement Learning-Based Redirection Controller for Efficient Redirected Walking in Virtual Maze Environment," in *Computer Graphics International Conference*, 2020, vol. 12221: Springer, Cham, pp. 33-45; doi: 10.1007/978-3-030-61864-3_4.

[17] M. Azmandian, R. Yahata, T. Grechkin, J. Thomas, and E. S. Rosenberg, "Validating Simulation-Based Evaluation of Redirected Walking Systems," *IEEE Transactions on Visualization and Computer Graphics,* vol. 28, no. 5, pp. 2288-2298, 2022, doi: 10.1109/TVCG.2022.3150466.

[18] T. Ko, L. Su, Y. Chang, K. Matsumoto, T. Narumi, and M. Hirose, "Evaluate Optimal Redirected Walking Planning Using Reinforcement Learning," in *2020 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct)*, 9-13 Nov. 2020, pp. 201-202; doi 10.1109/ISMAR-Adjunct51615.2020.00059.

[19] Z. Y. Chen, Y. J. Li, M. Wang, F. Steinicke, and Q. Zhao, "A Reinforcement Learning Approach to Redirected Walking with Passive Haptic Feedback," in *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 4-8 Oct. 2021, pp. 184-192; doi: 10.1109/ISMAR52148.2021.00033.

[20] Y. Chang, K. Matsumoto, T. Narumi, T. Tanikawa, and M. Hirose, "Redirection Controller Using Reinforcement Learning," *IEEE Access,* vol. 9, pp. 145083-145097, 2021, doi: 10.1109/ACCESS.2021.3118056.

[21] D. Y. Lee, Y. H. Cho, and I. K. Lee, "Real-time Optimal Planning for Redirected Walking Using Deep Q-Learning," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 23-27 March 2019, pp. 63-71; doi: 10.1109/VR.2019.8798121.

[22] E. O. Pyzer-Knapp *et al.*, "Accelerating materials discovery using artificial intelligence, high performance computing and robotics," *npj Computational Materials,* vol. 8, no. 1, p. 84, 2022, doi: 10.1038/s41524-022-00765-z.

[23] S. Bianchini, M. Müller, and P. Pelletier, "Artificial intelligence in science: An emerging general method of invention," *Research Policy,* vol. 51, no. 10, p. 104604, 2022, doi: 10.1016/j.respol.2022.104604.

[24] C. Hirt, Y. Kompis, C. Holz, and A. Kunz, "The Chaotic Behavior of Redirection – Revisiting Simulations in Redirected Walking," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 12-16 March 2022, pp. 524-533; doi 10.1109/VR51125.2022.00072.

[25] J. Paul and M. Barari, "Meta-analysis and traditional systematic literature reviews—What, why, when, where, and how?," *Psychology & Marketing,* vol. 39, no. 6, pp. 1099-1115, 2022, doi: 10.1002/mar.21657.

[26] R. van de Schoot *et al.*, "An open source machine learning framework for efficient and transparent systematic reviews," *Nature Machine Intelligence,* vol. 3, no. 2, pp. 125-133, 2021, doi: 10.1038/s42256-020-00287-7.

[27] F. Steinicke, G. Bruder, L. Kohli, J. Jerald, and K. Hinrichs, "Taxonomy and Implementation of Redirection Techniques for Ubiquitous Passive Haptic Feedback," in *2008 International Conference on Cyberworlds*, 22-24 Sept. 2008, pp. 217-223; doi: 10.1109/CW.2008.53.

[28] Y. J. Li, M. Wang, F. Steinicke, and Q. Zhao, "OpenRDW: A Redirected Walking Library and Benchmark with Multi-User, Learning-based Functionalities and State-of-the-art Algorithms," in *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 4-8 Oct. 2021, pp. 21-30; doi: 10.1109/ISMAR52148.2021.00016.

[29] M. Azmandian, T. Grechkin, M. Bolas, and E. Suma, "The redirected walking toolkit: a unified development platform for exploring large virtual environments," in *2016 IEEE 2nd Workshop on Everyday Virtual Reality (WEVR)*, 20-20 March 2016, pp. 9-14; doi: 10.1109/WEVR.2016.7859537.

[30] T. S. Rocco and M. S. Plakhotnik, "Literature Reviews, Conceptual Frameworks, and Theoretical Frameworks: Terms, Functions, and Distinctions," *Human Resource Development Review,* vol. 8, no. 1, pp. 120-130, 2009, doi: 10.1177/1534484309332617.

[31] D. Mendez, D. Graziotin, S. Wagner, and H. Seibold, "Open Science in Software Engineering," in *Contemporary Empirical Methods in Software Engineering*, M. Felderer and G. H. Travassos Eds. Cham: Springer International Publishing, 2020, pp. 477-501, doi: 10.1007/978-3-030-32489-6_17.

[32] E. Halilaj, A. Rajagopal, M. Fiterau, J. L. Hicks, T. J. Hastie, and S. L. Delp, "Machine learning in human movement biomechanics: Best practices, common pitfalls, and new opportunities," *Journal of biomechanics,* vol. 81, pp. 1-11, 2018, doi: 10.1016/j.jbiomech.2018.09.009.

[33] S. Badillo *et al.*, "An Introduction to Machine Learning," *Clinical Pharmacology & Therapeutics,* vol. 107, no. 4, pp. 871-885, 2020, doi: 10.1002/cpt.1796.

[34] Z. Munn, M. D. J. Peters, C. Stern, C. Tufanaru, A. McArthur, and E. Aromataris, "Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach," *BMC Medical Research Methodology,* vol. 18, no. 1, p. 143, 2018, doi: 10.1186/s12874-018-0611-x.

[35] G. M. Tawfik *et al.*, "A step by step guide for conducting a systematic review and meta-analysis with simulation data," *Tropical Medicine and Health,* vol. 47, no. 1, p. 46, 2019, doi: 10.1186/s41182-019-0165-6.

[36] K. Roberts, A. Dowell, and J.-B. Nie, "Attempting rigour and replicability in thematic analysis of qualitative research data; a case study of codebook development," *BMC Medical Research Methodology,* vol. 19, no. 1, p. 66, 2019, doi: 10.1186/s12874-019-0707-y.

[37] M. Vaismoradi, H. Turunen, and T. Bondas, "Content analysis and thematic analysis: Implications for conducting a qualitative descriptive study," *Nursing & Health Sciences,* vol. 15, no. 3, pp. 398-405, 2013, doi: 10.1111/nhs.12048.

[38] L. S. Nowell, J. M. Norris, D. E. White, and N. J. Moules, "Thematic Analysis:Striving to Meet the Trustworthiness Criteria," *International Journal of Qualitative Methods,* vol. 16, no. 1, p. 1609406917733847, 2017, doi: 10.1177/1609406917733847.

[39] D. Byrne, "A worked example of Braun and Clarke's approach to reflexive thematic analysis," *Quality & Quantity,* 2021, doi: 10.1007/s11135-021-01182-y.

[40] V. Interrante, B. Ries, and L. Anderson, "Seven League Boots: A New Metaphor for Augmented Locomotion through Moderately Large Scale Immersive Virtual Environments," in *2007 IEEE Symposium on 3D User interfaces*, 2007: IEEE, pp. 167 - 170; doi: 10.1109/3DUI.2007.340791.

[41] P. Schmitz, J. Hildebrandt, A. C. Valdez, L. Kobbelt, and M. Ziefle, "You Spin my Head Right Round: Threshold of Limited Immersion for Rotation Gains in Redirected Walking," *IEEE Transactions on Visualization and Computer Graphics,* vol. 24, no. 4, pp. 1623-1632, 2018, doi: 10.1109/TVCG.2018.2793671.

[42] A. C. Farr, T. Kleinschmidt, P. Yarlagadda, and K. Mengersen, "Wayfinding: A simple concept, a complex process," *Transport Reviews,* vol. 32, no. 6, pp. 715-743, 2012, doi: 10.1080/01441647.2012.712555.

[43] J. M. Wiener, S. J. Büchner, and C. Hölscher, "Taxonomy of human wayfinding tasks: A knowledge-based approach," *Spatial Cognition & Computation,* vol. 9, no. 2, pp. 152-165, 2009, ISSN: 1387-5868.

[44] Q. Sun, A. Patney, and F. Steinicke, "Redirected Walking in VR," in *Real VR–Immersive Digital Reality*, vol. 11900: Springer, 2020, pp. 285-292, doi: 10.1007/978-3-030-41816-8_12.

[45] G. Cirio, P. Vangorp, E. Chapoulie, M. Marchal, A. Lécuyer, and G. Drettakis, "Walking in a Cube: Novel Metaphors for Safely Navigating Large Virtual Environments in Restricted Real Workspaces," *IEEE Transactions on Visualization and Computer Graphics,* vol. 18, no. 4, pp. 546-554, 2012, doi: 10.1109/TVCG.2012.60.

[46] G. Bruder, F. Steinicke, B. Bolte, P. Wieland, H. Frenz, and M. Lappe, "Exploiting perceptual limitations and illusions to support walking through virtual environments in confined physical spaces," *Displays,* vol. 34, no. 2, pp. 132-141, 2013, doi: 10.1016/j.displa.2012.10.007.

[47] T. C. Peck, H. Fuchs, and M. C. Whitton, "Evaluation of Reorientation Techniques and Distractors for Walking in Large Virtual Environments," *IEEE Transactions on Visualization and Computer Graphics,* vol. 15, no. 3, pp. 383-394, 2009, doi: 10.1109/TVCG.2008.191.

[48] A. Borrego, J. Latorre, R. Llorens, M. Alcañiz, and E. Noé, "Feasibility of a walking virtual reality system for rehabilitation: objective and subjective parameters," *Journal of neuroengineering and rehabilitation,* vol. 13, no. 1, p. 68, 2016, doi: 10.1186/s12984-016-0174-1.

[49] B. Zhang, J. X. Zhang, S. Huang, L. Kong, and S. Wang, "Effects of load on the guidance of visual attention from working memory," *Vision Research,* vol. 51, no. 23, pp. 2356-2361, 2011, doi: 10.1016/j.visres.2011.09.008.

[50] D. Engel, C. Curio, L. Tcheang, B. Mohler, and H. H. Bülthoff, "A Psychophysically Calibrated Controller for Navigating through Large Environments in a Limited Free-Walking Space," in *Proceedings of the 2008 ACM symposium on Virtual reality software and technology*, Bordeaux, France, 2008: Association for Computing Machinery, pp. 157-164; doi: 10.1145/1450579.1450612.

[51] E. Hodgson, E. Bachmann, and T. Thrash, "Performance of redirected walking algorithms in a constrained virtual world," *IEEE Transactions on Visualization and Computer Graphics,* vol. 20, no. 4, pp. 579-587, 2014, doi: 10.1109/TVCG.2014.34.

[52] B. J. Baars and N. M. Gage, *Cognition, Brain, and Consciousness : Introduction to Cognitive Neuroscience*. San Diego, UNITED KINGDOM: Elsevier Science & Technology, 2010, doi: 10.1016/C2009-0-01556-6.

[53] A. Fontan, L. Lindgren, T. Pedale, C. Brorsson, F. Bergström, and J. Eriksson, "A reduced level of consciousness affects non-conscious processes," *NeuroImage,* vol. 244, p. 118571, 2021, doi: 10.1016/j.neuroimage.2021.118571.

[54] N. Ranasinghe *et al.*, "Season Traveller: Multisensory Narration for Enhancing the Virtual Reality Experience," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, Montreal QC, Canada, 2018: Association for Computing Machinery, Paper 577; doi: 10.1145/3173574.3174151.

[55] K. Cowan and S. Ketron, "A dual model of product involvement for effective virtual reality: The roles of imagination, co-creation, telepresence, and interactivity," *Journal of Business Research,* vol. 100, pp. 483-492, 2019, doi: 10.1016/j.jbusres.2018.10.063.

[56] S. S. Fisher, M. McGreevy, J. Humphries, and W. Robinett, "Virtual environment display system," in *Proceedings of the 1986 workshop on Interactive 3D graphics*, Chapel Hill, North Carolina, USA, 1987: Association for Computing Machinery, pp. 77–87; doi: 10.1145/319120.319127.

[57] S. O'Connor, "Virtual Reality and Avatars in Health care," *Clinical Nursing Research,* vol. 28, no. 5, pp. 523-528, 2019, doi: 10.1177/1054773819845824.

[58] C. S. Mon, K. M. Yap, and A. Ahmad, "A Preliminary Study on Requirements of Olfactory, Haptic and Audio Enabled Application for Visually Impaired in Edutainment," in *2019 IEEE 9th Symposium on Computer Applications & Industrial Electronics (ISCAIE)*, 27-28 April 2019, pp. 249-253; doi: 10.1109/ISCAIE.2019.8743738.

[59] S. S. Chance, F. Gaunet, A. C. Beall, and J. M. Loomis, "Locomotion Mode Affects the Updating of Objects Encountered During Travel: The Contribution of Vestibular and Proprioceptive Inputs to Path Integration," *Presence: Teleoperators and Virtual Environments,* vol. 7, no. 2, pp. 168-178, 1998, doi: 10.1162/105474698565659.

[60] K. Samperi, R. Beale, and N. Hawes, "Please keep off the grass: individual norms in virtual worlds," in *The 26th BCS Conference on Human Computer Interaction*, Birmingham, UK, 2012, pp. 375-380; doi: 10.14236/ewic/HCI2012.54.

[61] C. Wohlin, "Guidelines for snowballing in systematic literature studies and a replication in software engineering," in *Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering*, London,

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England, United Kingdom, 2014: Association for Computing Machinery, p. Article 38; doi: 10.1145/2601248.2601268.

[62] L. Kruse, E. Langbehn, and F. Steinicke, "I Can See on My Feet While Walking: Sensitivity to Translation Gains with Visible Feet," in *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Tuebingen/Reutlingen, Germany, 18-22 March 2018: IEEE, pp. 305-312; doi: 10.1109/VR.2018.8446216.

[63] L. L. Lemon and J. Hayes, "Enhancing trustworthiness of qualitative findings: Using Leximancer for qualitative data analysis triangulation," *The Qualitative Report,* vol. 25, no. 3, pp. 604-614, 2020, doi: 10.46743/2160-3715/2020.4222.

[64] U. Flick, "Triangulation in Data Collection," *The SAGE Handbook of Qualitative Data Collection*, U. Flick, Ed., London: SAGE Publications Ltd, 2018. [Online]. doi: 10.4135/9781526416070:

[65] H. Kyngäs, M. Kääriäinen, and S. Elo, "The Trustworthiness of Content Analysis," in *The Application of Content Analysis in Nursing Science Research*, H. Kyngäs, K. Mikkonen, and M. Kääriäinen Eds. Cham: Springer International Publishing, 2020, pp. 41-48, doi: 10.1007/978-3-030-30199-6_5.

[66] B. Saunders *et al.*, "Saturation in qualitative research: exploring its conceptualization and operationalization," *Quality & Quantity,* vol. 52, no. 4, pp. 1893-1907, 2018, doi: 10.1007/s11135-017-0574-8.

[67] W. Xu and K. Zammit, "Applying Thematic Analysis to Education: A Hybrid Approach to Interpreting Data in Practitioner Research," *International Journal of Qualitative Methods,* vol. 19, 2020, doi: 10.1177/1609406920918810.

[68] T. Schmelter, L. Hernadi, M. A. Störmer, F. Steinicke, and K. Hildebrand, "Interaction Based Redirected Walking," *Proc. ACM Comput. Graph. Interact. Tech.,* vol. 4, no. 1, pp. 1 - 16, 2021, Art no. 9, doi: 10.1145/3451264.

[69] C. Hutton, S. Ziccardi, J. Medina, and E. S. Rosenberg, "Individualized Calibration of Rotation Gain Thresholds for Redirected Walking," in *ICAT-EGVE*, 2018, pp. 61-64; doi: 10.2312/egve.20181315.

[70] W. Chen, N. Ladevèze, W. Hu, S. Ou, and P. Bourdot, "Comparison Between the Methods of Adjustment and Constant Stimuli for the Estimation of Redirection Detection Thresholds," in *Virtual Reality and Augmented Reality*, Cham, P. Bourdot, V. Interrante, L. Nedel, N. Magnenat-Thalmann, and G. Zachmann, Eds., 2019: Springer International Publishing, pp. 226-245; doi: 10.1007/978-3-030-31908-3_14.

[71] Y. Li, M. Wang, D. Jin, F. Steinicke, and Q. Zhao, "Effects of virtual environment and self-representations on perception and physical performance in redirected jumping," *Virtual Reality & Intelligent Hardware,* vol. 3, no. 6, pp. 451-469, 2021, doi: 10.1016/j.vrih.2021.06.003.

[72] X. Liu and L. Wang, "Redirected jumping in virtual scenes with alleys," *Virtual Reality & Intelligent Hardware,* vol. 3, no. 6, pp. 470-483, 2021, doi: 10.1016/j.vrih.2021.06.004.

[73] Y. Hoshikawa, K. Fujita, K. Takashima, M. Fjeld, and Y. Kitamura, "RedirectedDoors: Redirection While Opening Doors in Virtual Reality," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 12-16 March 2022, pp. 464-473; doi 10.1109/VR51125.2022.00066.

[74] K. Krippendorff, "Computing Krippendorff's Alpha-Reliability," 2011. Accessed: 24/3/23. [Online]. Available: https://repository.upenn.edu/asc_papers/43

[75] K. Krippendorff, "Estimating the Reliability, Systematic Error and Random Error of Interval Data," *Educational and Psychological Measurement,* vol. 30, no. 1, pp. 61-70, 1970, doi: 10.1177/001316447003000105.

[76] K. Krippendorff, "Content Analysis: An Introduction to Its Methodology," Fourth Edition ed. Thousand Oaks, California: SAGE Publications, Inc., 2019. [Online], doi: 10.4135/9781071878781.

[77] B. Williams, G. Narasimham, T. P. McNamara, T. H. Carr, J. J. Rieser, and B. Bodenheimer, "Updating Orientation in Large Virtual Environments Using Scaled Translational Gain," in *Proceedings of the 3rd Symposium on Applied Perception in Graphics and Visualization*, Boston, Massachusetts, USA, 2006: Association for Computing Machinery, pp. 21-28; doi: 10.1145/1140491.1140495.

[78] F. Steinicke, G. Bruder, K. Hinrichs, and A. Steed, "Gradual transitions and their effects on presence and distance estimation," *Computers & Graphics,* vol. 34, no. 1, pp. 26-33, 2010, doi: 10.1016/j.cag.2009.12.003.

[79] T. C. Peck, H. Fuchs, and M. C. Whitton, "An evaluation of navigational ability comparing Redirected Free Exploration with Distractors to Walking-in-Place and joystick locomotion interfaces," in *2011 IEEE Virtual Reality Conference*, 2011: IEEE, pp. 55-62; doi: 10.1109/VR.2011.5759437.

[80] B. Williams *et al.*, "Exploring Large Virtual Environments with an HMD When Physical Space is Limited," in *Proceedings of the 4th symposium on Applied perception in graphics and visualization*, Tubingen, Germany, 2007: Association for Computing Machinery, pp. 41-48; doi: 10.1145/1272582.1272590.

[81] C. T. Neth, J. L. Souman, D. Engel, U. Kloos, H. H. Bulthoff, and B. J. Mohler, "Velocity-Dependent Dynamic Curvature Gain for Redirected Walking," *IEEE Transactions on Visualization and Computer Graphics,* vol. 18, no. 7, pp. 1041-1052, 2012, doi: 10.1109/TVCG.2011.275.

[82] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe, "Estimation of Detection Thresholds for Redirected Walking Techniques," *IEEE Transactions on Visualization and Computer Graphics,* vol. 16, no. 1, pp. 17-27, 2010, doi: 10.1109/TVCG.2009.62.

[83] E. Suma, S. Clark, D. Krum, S. Finkelstein, M. Bolas, and Z. Warte, "Leveraging change blindness for redirection in virtual environments," in *2011 IEEE Virtual Reality Conference*, Singapore, 2011: IEEE, pp. 159-166; doi 10.1109/VR.2011.5759455.

[84] G. Cirio, M. Marchal, T. Regia-Corte, and A. Lécuyer, "The Magic Barrier Tape: A Novel Metaphor for Infinite Navigation in Virtual Worlds with a Restricted Walking Workspace," in *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology*, Kyoto, Japan, 2009: Association for Computing Machinery, pp. 155-162; doi: 10.1145/1643928.1643965.

[85] L. A. Sjolund, J. W. Kelly, and T. P. McNamara, "Optimal combination of environmental cues and path integration during navigation," *Memory & cognition,* vol. 46, no. 1, pp. 89-99, 2018, doi: 10.3758/s13421-017-0747-7.

[86] R. A. Paris, T. P. McNamara, J. J. Rieser, and B. Bodenheimer, "A comparison of methods for navigation and wayfinding in large virtual environments using walking," in *2017 IEEE Virtual Reality (VR)*, 2017: IEEE, pp. 261-262; doi 10.1109/VR.2017.7892276.

[87] M. Nogalski and W. Fohl, "Acoustic redirected walking with auditory cues by means of wave field synthesis," in *2016 IEEE Virtual Reality (VR)*, 2016: IEEE, pp. 245-246; doi: 10.1109/VR.2016.7504745.

[88] T. Nescher, Y.-Y. Huang, and A. Kunz, "Planning redirection techniques for optimal free walking experience using model predictive control," in *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, 2014: IEEE, pp. 111-118; doi: 10.1109/3DUI.2014.6798851.

[89] S. Serafin, N. C. Nilsson, E. Sikstrom, A. De Goetzen, and R. Nordahl, "Estimation of detection thresholds for acoustic based redirected walking techniques," in *2013 IEEE Virtual Reality (VR)*, 2013: IEEE, pp. 161-162; doi: 10.1109/VR.2013.6549412.

[90] J. Marín-Morales *et al.*, "Real vs. immersive-virtual emotional experience: Analysis of psycho-physiological patterns in a free exploration of an art museum," *PLOS ONE,* vol. 14, no. 10, pp. 1-24, 2019, doi: 10.1371/journal.pone.0223881.

[91] M. A. Zmuda, J. L. Wonser, E. R. Bachmann, and E. Hodgson, "Optimizing Constrained-Environment Redirected Walking Instructions Using Search Techniques," *IEEE Transactions on Visualization and Computer Graphics,* vol. 19, no. 11, pp. 1872-1884, 2013, doi: 10.1109/TVCG.2013.88.

[92] J. Yang, C. Holz, E. Ofek, and A. D. Wilson, "DreamWalker: Substituting Real-World Walking Experiences with a Virtual Reality," in *Proceedings of the 32nd Annual ACM Symposium*

on User Interface Software and Technology, New Orleans, LA, USA, 2019: Association for Computing Machinery, pp. 1093–1107; doi: 10.1145/3332165.3347875.

[93] N. Rewkowski, A. Rungta, M. Whitton, and M. Lin, "Evaluating the Effectiveness of Redirected Walking with Auditory Distractors for Navigation in Virtual Environments," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Osaka, Japan, 2019: IEEE, pp. 395-404; doi: 10.1109/VR.2019.8798286.

[94] L. Bölling, N. Stein, F. Steinicke, and M. Lappe, "Shrinking Circles: Adaptation to Increased Curvature Gain in Redirected Walking," *IEEE Transactions on Visualization and Computer Graphics,* vol. 25, no. 5, pp. 2032-2039, 2019, doi: 10.1109/TVCG.2019.2899228.

[95] R. Cools and A. L. Simeone, "Investigating the effect of distractor interactivity for redirected walking in virtual reality," in *Symposium on Spatial User Interaction*, New Orleans, LA, USA, 2019: Association for Computing Machinery, pp. 1-5; doi: 10.1145/3357251.3357580.

[96] P. Abtahi, M. Gonzalez-Franco, E. Ofek, and A. Steed, "I'm a Giant: Walking in Large Virtual Environments at High Speed Gains," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, Glasgow, Scotland Uk, 2019: Association for Computing Machinery, pp. 1-13; doi: 10.1145/3290605.3300752.

[97] S. Jung, C. W. Borst, S. Hoermann, and R. W. Lindeman, "Redirected Jumping: Perceptual Detection Rates for Curvature Gains," in *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, New Orleans, LA, USA, 2019: Association for Computing Machinery, pp. 1085-1092; doi: 10.1145/3332165.3347868.

[98] K. Matsumoto, T. Narumi, Y. Ban, Y. Yanase, T. Tanikawa, and M. Hirose, "Unlimited Corridor: A Visuo-Haptic Redirection System," in *The 17th International Conference on Virtual-Reality Continuum and its Applications in Industry*, Brisbane, QLD, Australia, 2019: Association for Computing Machinery, pp. 1-9; doi: 10.1145/3359997.3365705.

[99] N. L. Williams and T. C. Peck, "Estimation of Rotation Gain Thresholds Considering FOV, Gender, and Distractors," *IEEE Transactions on Visualization and Computer Graphics,* vol. 25, no. 11, pp. 3158-3168, 2019, doi: 10.1109/TVCG.2019.2932213.

[100] B. Williams-Sanders, T. Carr, G. Narasimham, T. McNamara, J. Rieser, and B. Bodenheimer, "Scaling Gain and Eyeheight While Locomoting in a Large VE," in *International Conference on Human-Computer Interaction*, 2019: Springer, Cham, pp. 277-298; doi: 10.1007/978-3-030-21607-8_22.

[101] J. Auda, M. Pascher, and S. Schneegass, "Around the (Virtual) World: Infinite Walking in Virtual Reality Using Electrical Muscle Stimulation," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 2019: Association for Computing Machinery, pp. 1-8; doi: 10.1145/3290605.3300661.

[102] E. R. Bachmann, E. Hodgson, C. Hoffbauer, and J. Messinger, "Multi-User Redirected Walking and Resetting Using Artificial Potential Fields," *IEEE Transactions on Visualization and Computer Graphics,* vol. 25, no. 5, pp. 2022-2031, 2019, doi: 10.1109/TVCG.2019.2898764.

[103] E. Langbehn, F. Steinicke, P. Koo-Poeggel, L. Marshall, and G. Bruder, "Stimulating the Brain in VR: Effects of Transcranial Direct-Current Stimulation on Redirected Walking," in *ACM Symposium on Applied Perception 2019*, Barcelona, Spain, 2019: Association for Computing Machinery, pp. 1-9; doi: 10.1145/3343036.3343125.

[104] E. Langbehn, F. Steinicke, M. Lappe, G. F. Welch, and G. Bruder, "In the Blink of an Eye: Leveraging Blink-Induced Suppression for Imperceptible Position and Orientation Redirection in Virtual Reality," *ACM Transactions on Graphics (TOG),* vol. 37, no. 4, pp. 1-11, 2018, Art no. 66, doi: 10.1145/3197517.3201335.

[105] E. Langbehn, P. Lubos, G. Bruder, and F. Steinicke, "Bending the Curve: Sensitivity to Bending of Curved Paths and Application in Room-Scale VR," *IEEE Transactions on Visualization and Computer Graphics,* vol. 23, no. 4, pp. 1389-1398, 2017, doi: 10.1109/TVCG.2017.2657220.

[106] H. Chen and H. Fuchs, "Towards Imperceptible Redirected Walking: Integrating a Distractor into the Immersive Experience," in *Proceedings of the 21st ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*, San Francisco, California, 2017: Association for Computing Machinery, pp. 1-2; doi: 10.1145/3023368.3036844.

[107] Y. Joshi and C. Poullis, "Inattentional Blindness for Redirected Walking Using Dynamic Foveated Rendering," *IEEE Access,* vol. 8, pp. 39013-39024, 2020, doi: 10.1109/ACCESS.2020.2975032.

[108] G. Wilson, M. McGill, M. Jamieson, J. R. Williamson, and S. A. Brewster, "Object Manipulation in Virtual Reality Under Increasing Levels of Translational Gain," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, 2018: Association for Computing Machinery, pp. 1-13; doi: 10.1145/3173574.3173673.

[109] Q. Sun *et al.*, "Towards Virtual Reality Infinite Walking: Dynamic Saccadic Redirection," *ACM Trans. Graph.,* vol. 37, no. 4, pp. 1-13, 2018, Art no. 67, doi: 10.1145/3197517.3201294.

[110] G. Bruder, V. Interrante, L. Phillips, and F. Steinicke, "Redirecting Walking and Driving for Natural Navigation in Immersive Virtual Environments," *IEEE Transactions on Visualization and Computer Graphics,* vol. 18, no. 4, pp. 538-545, 2012, doi: 10.1109/TVCG.2012.55.

[111] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey, "Locomotion in virtual reality for room scale tracked areas," *International Journal of Human-Computer Studies,* vol. 122, pp. 38-49, 2019, doi: 10.1016/j.ijhcs.2018.08.002.

[112] Y. Rothacher, A. Nguyen, B. Lenggenhager, A. Kunz, and P. Brugger, "Visual capture of gait during redirected walking," *Scientific Reports,* vol. 8, no. 1, pp. 1-13, 2018, doi: 10.1038/s41598-018-36035-6.

[113] T. Grechkin, J. Thomas, M. Azmandian, M. Bolas, and E. Suma, "Revisiting Detection Thresholds for Redirected Walking: Combining Translation and Curvature Gains," in *Proceedings of the ACM Symposium on Applied Perception*, Anaheim, California, 2016: Association for Computing Machinery, pp. 113–120; doi: 10.1145/2931002.2931018.

[114] E. Hodgson and E. Bachmann, "Comparing Four Approaches to Generalized Redirected Walking: Simulation and Live User Data," *IEEE Transactions on Visualization and Computer Graphics,* vol. 19, no. 4, pp. 634-643, 2013, doi: 10.1109/TVCG.2013.28.

[115] M. McCullough *et al.*, "Myo Arm: Swinging to Explore a VE," in *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception*, Tübingen, Germany, 2015: Association for Computing Machinery, pp. 107–113; doi: 10.1145/2804408.2804416.

[116] F. Meyer, M. Nogalski, and W. Fohl, "Detection thresholds in audio-visual redirected walking," in *Proc. Sound and Music Comp. Conf.(SMC)*, 2016, vol. 16, no. 1, pp. 1-7. [Online]. Available: https://core.ac.uk/download/pdf/144846422.pdf.

[117] N. C. Nilsson, E. Suma, R. Nordahl, M. Bolas, and S. Serafin, "Estimation of detection thresholds for audiovisual rotation gains," in *2016 IEEE Virtual Reality (VR)*, 19-23 March 2016, pp. 241-242; doi: 10.1109/VR.2016.7504743.

[118] R. Nordahl, "Increasing the motion of users in photorealistic virtual environments by utilizing auditory rendering of the environment and ego-motion," in *Proceedings of the 9th International Workshop on Presence*, Cleveland State University, 2006: International Society for Presence Research, Cleveland State University, pp. 57-63. [Online]. Available:https://vbn.aau.dk/ws/portalfiles/portal/11635150/nordahl_presence_2007.pdf.

[119] R. Nordahl, S. Serafin, L. Turchet, and N. C. Nilsson, "A multimodal architecture for simulating natural interactive walking in virtual environments," *PsychNology Journal,* vol. 9, no. 3, pp. 245 - 268, 2011. [Online]. Available: https://vbn.aau.dk/ws/portalfiles/portal/68344243/PSYCHNOLOGY_JOURNAL_9_3_NORDAHL_A_multimodal_architectu

re_for_simulating_natural_interactive_walking_in_virtual_environments.pdf.
[120] A. L. Simeone, E. Velloso, and H. Gellersen, "Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences," in *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, Seoul, Republic of Korea, 2015: Association for Computing Machinery, pp. 3307–3316; doi: 10.1145/2702123.2702389.
[121] K. Vasylevska and H. Kaufmann, "Towards efficient spatial compression in self-overlapping virtual environments," in *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, Los Angeles, CA, USA, 18-19 March 2017, pp. 12-21; doi: 10.1109/3DUI.2017.7893312.
[122] K. Vasylevska, H. Kaufmann, M. Bolas, and E. A. Suma, "Flexible spaces: Dynamic layout generation for infinite walking in virtual environments," in *2013 IEEE Symposium on 3D User Interfaces (3DUI)*, Orlando, FL, USA, 2013: IEEE, pp. 39-42; doi: 10.1109/3DUI.2013.6550194.
[123] L. E. Buck, J. J. Rieser, G. Narasimham, and B. Bodenheimer, "Interpersonal Affordances and Social Dynamics in Collaborative Immersive Virtual Environments: Passing Together Through Apertures," *IEEE Transactions on Visualization and Computer Graphics,* vol. 25, no. 5, pp. 2123-2133, 2019, doi: 10.1109/TVCG.2019.2899232.
[124] I. Podkosova and H. Kaufmann, "Mutual Collision Avoidance during Walking in Real and Collaborative Virtual Environments," in *Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games*, Montreal, Quebec, Canada, 2018: Association for Computing Machinery, pp. 1-9; doi: 10.1145/3190834.3190845.
[125] C. Mousas, A. Koilias, D. Anastasiou, B. Rekabdar, and C. Anagnostopoulos, "Effects of Self-Avatar and Gaze on Avoidance Movement Behavior," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Osaka, Japan, 23-27 March 2019: IEEE, pp. 726-734; doi: 10.1109/VR.2019.8798043.
[126] F. Berton, A. Olivier, J. Bruneau, L. Hoyet, and J. Pettre, "Studying Gaze Behaviour during Collision Avoidance with a Virtual Walker: Influence of the Virtual Reality Setup," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Osaka, Japan, 23-27 March 2019: IEEE, pp. 717-725; doi: 10.1109/VR.2019.8798204.
[127] B. Mohler, J. Campos, M. Weyel, and H. H. Bülthoff, "Gait Parameters while Walking in a Head-mounted Display Virtual Environment and the Real World," in *13th Eurographics Symposium on Virtual Environments and 10th Immersive Projection Technology Workshop (IPT-EGVE 2007)*, 2007: The Eurographics Association, pp. 85-88; doi: 10.2312/PE/VE2007Short/085-088.
[128] D. Min, D. Lee, Y. Cho, and I. Lee, "Shaking Hands in Virtual Space: Recovery in Redirected Walking for Direct Interaction between Two Users," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Atlanta, GA, USA, 22-26 March 2020: IEEE, pp. 164-173; doi: 10.1109/VR46266.2020.00035.
[129] E. Hodgson, E. R. Bachmann, D. Vincent, M. Zmuda, D. Waller, and J. Calusdian, "WeaVR: a self-contained and wearable immersive virtual environment simulation system," *Behavior Research Methods,* vol. 47, no. 1, pp. 296-307, 2015, doi: 10.3758/s13428-014-0463-1.
[130] F. Berton, L. Hoyet, A. Olivier, J. Bruneau, O. L. Meur, and J. Pettre, "Eye-Gaze Activity in Crowds: Impact of Virtual Reality and Density," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Atlanta, GA, USA, 22-26 March 2020: IEEE, pp. 322-331; doi: 10.1109/VR46266.2020.00052.
[131] O. Janeh, N. Katzakis, J. Tong, and F. Steinicke, "Infinity Walk in VR: Effects of Cognitive Load on Velocity during Continuous Long-Distance Walking," in *ACM Symposium on Applied Perception 2019*, Barcelona, Spain, 2019: Association for Computing Machinery, pp. 1-9; doi: 10.1145/3343036.3343119.
[132] D. Checa and A. Bustillo, "Advantages and limits of virtual reality in learning processes: Briviesca in the fifteenth century," *Virtual Reality,* vol. 24, no. 1, pp. 151-161, 2020, doi: 10.1007/s10055-019-00389-7.
[133] A. Nguyen, P. Wüest, and A. Kunz, "Human Following Behavior In Virtual Reality," in *26th ACM Symposium on Virtual Reality Software and Technology*, Virtual Event, Canada, 2020: Association for Computing Machinery, pp. 1-3; doi: 10.1145/3385956.3422099.
[134] M. Nelson, A. Koilias, S. Gubbi, and C. Mousas, "Within a Virtual Crowd: Exploring Human Movement Behavior during Immersive Virtual Crowd Interaction," in *The 17th International Conference on Virtual-Reality Continuum and its Applications in Industry*, Brisbane, QLD, Australia, 2019: Association for Computing Machinery, pp. 1-10; doi: 10.1145/3359997.3365709.
[135] P. Agethen, V. S. Sekar, F. Gaisbauer, T. Pfeiffer, M. Otto, and E. Rukzio, "Behavior Analysis of Human Locomotion in the Real World and Virtual Reality for the Manufacturing Industry," *ACM Transactions on Applied Perception (TAP),* vol. 15, no. 3, pp. 1-19, 2018, Art no. 20, doi: 10.1145/3230648.
[136] D. Dewez, L. Hoyet, A. Lécuyer, and F. Argelaguet, "Studying the Inter-Relation Between Locomotion Techniques and Embodiment in Virtual Reality," in *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, Porto de Galinhas, Brazil, 9-13 Nov. 2020: IEEE, pp. 452-461; doi: 10.1109/ISMAR50242.2020.00070.
[137] M. Rietzler, J. Gugenheimer, T. Hirzle, M. Deubzer, E. Langbehn, and E. Rukzio, "Rethinking Redirected Walking: On the Use of Curvature Gains Beyond Perceptual Limitations and Revisiting Bending Gains," in *2018 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, Munich, Germany, 16-20 Oct. 2018: IEEE, pp. 115-122; doi: 10.1109/ISMAR.2018.00041.
[138] A. Nguyen, Y. Rothacher, B. Lenggenhager, P. Brugger, and A. Kunz, "Effect of Sense of Embodiment on Curvature Redirected Walking Thresholds," in *ACM Symposium on Applied Perception 2020*, Virtual Event, USA, 2020: Association for Computing Machinery, pp. 1-5; doi: 10.1145/3385955.3407932.
[139] A. Nguyen *et al.*, "Effect of Cognitive Load on Curvature Redirected Walking Thresholds," in *26th ACM Symposium on Virtual Reality Software and Technology*, Virtual Event, Canada, 2020: Association for Computing Machinery, pp. 1-5; doi: 10.1145/3385956.3418950.
[140] A. Nguyen and A. Kunz, "Discrete scene rotation during blinks and its effect on redirected walking algorithms," in *Proceedings of the 24th ACM Symposium on Virtual Reality Software and Technology*, Tokyo, Japan, 2018: Association for Computing Machinery, pp. 1-10; doi: 10.1145/3281505.3281515.
[141] E. Suma, S. Finkelstein, M. Reid, S. Babu, A. Ulinski, and L. F. Hodges, "Evaluation of the Cognitive Effects of Travel Technique in Complex Real and Virtual Environments," *IEEE Transactions on Visualization and Computer Graphics,* vol. 16, no. 4, pp. 690-702, 2010, doi: 10.1109/TVCG.2009.93.
[142] C. A. Zanbaka, B. C. Lok, S. V. Babu, A. C. Ulinski, and L. F. Hodges, "Comparison of Path Visualizations and Cognitive Measures Relative to Travel Technique in a Virtual Environment," *IEEE Transactions on Visualization and Computer Graphics,* vol. 11, no. 6, pp. 694-705, 2005, doi: 10.1109/TVCG.2005.92.
[143] M. Usoh *et al.*, "Walking > Walking-in-Place > Flying, in Virtual Environments," in *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, Los Angeles, CA USA, 1999: ACM Press/Addison-Wesley Publishing Co., pp. 359–364; doi: 10.1145/311535.311589.
[144] R. A. Ruddle and S. Lessels, "The benefits of using a walking interface to navigate virtual environments," *ACM Trans. Comput.-Hum. Interact.,* vol. 16, no. 1, pp. 1-18, 2009, Art no. 5, doi: 10.1145/1502800.1502805.
[145] S. Razzaque, Z. Kohn, and M. C. Whitton, *Redirected Walking*. Eurographics Association, 2001, doi: 10.2312/egs.20011036.
[146] M. Zank and A. Kunz, "Eye tracking for locomotion prediction in redirected walking," in *2016 IEEE Symposium on 3D User*

Interfaces (3DUI), Greenville, SC, USA, 19-20 March 2016: IEEE, pp. 49-58; doi: 10.1109/3DUI.2016.7460030.

[147] S. Freitag, D. Rausch, and T. Kuhlen, "Reorientation in virtual environments using interactive portals," in *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, Minneapolis, MN, USA, 29-30 March 2014: IEEE, pp. 119-122; doi: 10.1109/3DUI.2014.6798852.

[148] E. A. Suma, Z. Lipps, S. Finkelstein, D. M. Krum, and M. Bolas, "Impossible Spaces: Maximizing Natural Walking in Virtual Environments with Self-Overlapping Architecture," *IEEE Transactions on Visualization and Computer Graphics,* vol. 18, no. 4, pp. 555-564, 2012, doi: 10.1109/TVCG.2012.47.

[149] T. Y. Grechkin, J. M. Plumert, and J. K. Kearney, "Dynamic Affordances in Embodied Interactive Systems: The Role of Display and Mode of Locomotion," *IEEE Transactions on Visualization and Computer Graphics,* vol. 20, no. 4, pp. 596-605, 2014, doi: 10.1109/TVCG.2014.18.

[150] M. Marchal, A. Lécuyer, G. Cirio, L. Bonnet, and M. Emily, "Walking up and down in immersive virtual worlds: Novel interactive techniques based on visual feedback," in *2010 IEEE Symposium on 3D User Interfaces (3DUI)*, Waltham, MA, USA, 20-21 March 2010: IEEE, pp. 19-26; doi: 10.1109/3DUI.2010.5446238.

[151] K. Matsumoto, T. Narumi, T. Tanikawa, and M. Hirose, "Walking uphill and downhill: redirected walking in the vertical direction," in *ACM SIGGRAPH 2017 Posters*, Los Angeles, California, 2017: Association for Computing Machinery, pp. 1-2; doi: 10.1145/3102163.3102227.

[152] K. Matsumoto, Y. Ban, T. Narumi, T. Tanikawa, and M. Hirose, "Curvature manipulation techniques in redirection using haptic cues," in *2016 IEEE Symposium on 3D User Interfaces (3DUI)*, Greenville, SC, USA, 19-20 March 2016: IEEE, pp. 105-108; doi: 10.1109/3DUI.2016.7460038.

[153] E. A. Suma, S. Babu, and L. F. Hodges, "Comparison of Travel Techniques in a Complex, Multi-Level 3D Environment," in *2007 IEEE Symposium on 3D User Interfaces*, Charlotte, NC, USA, 10-11 March 2007: IEEE, p. 1; doi: 10.1109/3DUI.2007.340788.

[154] R. A. Ruddle, E. Volkova, and H. H. Bülthoff, "Learning to walk in virtual reality," *ACM Trans. Appl. Percept.,* vol. 10, no. 2, pp. 1-17, 2013, Art no. 11, doi: 10.1145/2465780.2465785.

[155] M. Nabiyouni, A. Saktheeswaran, D. A. Bowman, and A. Karanth, "Comparing the performance of natural, semi-natural, and non-natural locomotion techniques in virtual reality," in *2015 IEEE Symposium on 3D User Interfaces (3DUI)*, Arles, France, 23-24 March 2015: IEEE, pp. 3-10; doi: 10.1109/3DUI.2015.7131717.

[156] N. Nitzsche, U. D. Hanebeck, and G. Schmidt, "Motion Compression for Telepresent Walking in Large Target Environments," *PRESENCE: Teleoperators & Virtual Environments,* Article vol. 13, no. 1, pp. 44-60, 2004, doi: 10.1162/105474604774048225.

[157] F. Steinicke, G. Bruder, K. Hinrichs, and A. Steed, "Presence-Enhancing Real Walking User Interface for First-Person Video Games," in *Proceedings of the 2009 ACM SIGGRAPH Symposium on Video Games*: Association for Computing Machinery, 2009, pp. 111–118.

[158] E. Hodgson, E. Bachmann, and D. Waller, "Redirected walking to explore virtual environments: Assessing the potential for spatial interference," *ACM Trans. Appl. Percept.,* vol. 8, no. 4, pp. 1-22, 2008, Art no. 22, doi: 10.1145/2043603.2043604.

[159] T. C. Peck, H. Fuchs, and M. C. Whitton, "Improved Redirection with Distractors: A large-scale-real-walking locomotion interface and its effect on navigation in virtual environments," in *2010 IEEE Virtual Reality Conference (VR)*, Boston, MA, USA, 20-24 March 2010: IEEE, pp. 35-38; doi: 10.1109/VR.2010.5444816.

[160] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe, "Analyses of Human Sensitivity to Redirected Walking," in *Proceedings of the 2008 ACM symposium on Virtual reality software and technology*, Bordeaux, France, 2008: Association for Computing Machinery, pp. 149–156; doi: 10.1145/1450579.1450611.

[161] G. Bruder, F. Steinicke, K. H. Hinrichs, and M. Lappe, "Reorientation During Body Turns," in *EGVE/ICAT/EuroVR*, 2009: Citeseer, pp. 145-152. [Online]. Available: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.182.3848&rep=rep1&type=pdf.

[162] R. Zhang and S. A. Kuhl, "Human sensitivity to dynamic rotation gains in head-mounted displays," in *Proceedings of the ACM Symposium on Applied Perception*, Dublin, Ireland, 2013: Association for Computing Machinery, pp. 71–74; doi: 10.1145/2492494.2492514.

[163] X. Xie *et al.*, "A system for exploring large virtual environments that combines scaled translational gain and interventions," in *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization*, Los Angeles, California, 2010: Association for Computing Machinery, pp. 65–72; doi: 10.1145/1836248.1836260.

[164] G. Bruder, P. Lubos, and F. Steinicke, "Cognitive Resource Demands of Redirected Walking," *IEEE Transactions on Visualization and Computer Graphics,* vol. 21, no. 4, pp. 539-544, 09 February 2015, doi: 10.1109/TVCG.2015.2391864.

[165] S. Freitag, B. Weyers, and T. W. Kuhlen, "Examining Rotation Gain in CAVE-like Virtual Environments," *IEEE Transactions on Visualization and Computer Graphics,* vol. 22, no. 4, pp. 1462-1471, 2016, doi: 10.1109/TVCG.2016.2518298.

[166] E. A. Suma, D. M. Krum, S. Finkelstein, and M. Bolas, "Effects of redirection on spatial orientation in real and virtual environments," in *2011 IEEE Symposium on 3D User Interfaces (3DUI)*, Singapore, 19-20 March 2011: IEEE, pp. 35-38; doi: 10.1109/3DUI.2011.5759214.

[167] E. Langbehn, P. Lubos, and F. Steinicke, "Evaluation of Locomotion Techniques for Room-Scale VR: Joystick, Teleportation, and Redirected Walking," in *Proceedings of the Virtual Reality International Conference - Laval Virtual*, Laval, France, 2018: Association for Computing Machinery, pp. 1-9; doi: 10.1145/3234253.3234291.

[168] B. Williams, S. Bailey, G. Narasimham, M. Li, and B. Bodenheimer, "Evaluation of walking in place on a Wii balance board to explore a virtual environment," *ACM Trans. Appl. Percept.,* vol. 8, no. 3, pp. 1-14, 2011, Art no. 19, doi: 10.1145/2010325.2010329.

[169] J. Feasel, M. C. Whitton, and J. D. Wendt, "LLCM-WIP: Low-Latency, Continuous-Motion Walking-in-Place," in *2008 IEEE Symposium on 3D User Interfaces*, Reno, NV, USA, 8-9 March 2008: IEEE, pp. 97-104; doi: 10.1109/3DUI.2008.4476598.

[170] P. T. Wilson, W. Kalescky, A. MacLaughlin, and B. Williams, "VR locomotion: walking > walking in place > arm swinging," in *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry - Volume 1*, Zhuhai, China, 2016: Association for Computing Machinery, pp. 243–249; doi: 10.1145/3013971.3014010.

[171] J. L. Souman *et al.*, "CyberWalk: Enabling unconstrained omnidirectional walking through virtual environments," *ACM Trans. Appl. Percept.,* vol. 8, no. 4, pp. 1-22, 2008, Art no. 25, doi: 10.1145/2043603.2043607.

[172] E. A. Suma, S. L. Finkelstein, S. Clark, P. Goolkasian, and L. F. Hodges, "Effects of travel technique and gender on a divided attention task in a virtual environment," in *2010 IEEE Symposium on 3D User Interfaces (3DUI)*, Waltham, MA, USA, 20-21 March 2010: IEEE, pp. 27-34; doi: 10.1109/3DUI.2010.5444726.

[173] B. Bolte, F. Steinicke, and G. Bruder, "The jumper metaphor: an effective navigation technique for immersive display setups," in *Proceedings of the Virtual Reality International Conference (VRIC)*, Laval, France, 2011, vol. 1, pp. 1-7. [Online]. Available: http://basilic.informatik.uni-hamburg.de/Publications/2011/BBS11a.

[174] J. Bhandari, S. Tregillus, and E. Folmer, "Legomotion: scalable walking-based virtual locomotion," in *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, Gothenburg, Sweden, 2017: Association for Computing Machinery, pp. 1-8; doi: 10.1145/3139131.3139133.

[175] G. Bruder, F. Steinicke, P. Wieland, and M. Lappe, "Tuning Self-Motion Perception in Virtual Reality with Visual

Illusions," *IEEE Transactions on Visualization and Computer Graphics,* vol. 18, no. 7, pp. 1068-1078, 2012, doi: 10.1109/TVCG.2011.274.

[176] R. Zhang, B. Li, and S. A. Kuhl, "Human Sensitivity to Dynamic Translational Gains in Head-Mounted Displays," in *Proceedings of the 2nd ACM symposium on Spatial user interaction*, Honolulu, Hawaii, USA, 2014: Association for Computing Machinery, pp. 62–65; doi: 10.1145/2659766.2659783.

[177] M. Zank and A. Kunz, "Where are you going? Using human locomotion models for target estimation," *The Visual Computer,* vol. 32, no. 10, pp. 1323-1335, 2016, doi: 10.1007/s00371-016-1229-9.

[178] W. E. Marsh, J. W. Kelly, V. J. Dark, and J. H. Oliver, "Cognitive demands of semi-natural virtual locomotion," *Presence: Teleoperators and Virtual Environments,* vol. 22, no. 3, pp. 216-234, 2013, doi: 10.1162/PRES_a_00152.

[179] M. Meehan, B. Insko, M. Whitton, and F. P. Brooks, "Physiological measures of presence in stressful virtual environments," *ACM Trans. Graph.,* vol. 21, no. 3, pp. 645–652, 2002, doi: 10.1145/566654.566630.

[180] Q. Sun, L.-Y. Wei, and A. Kaufman, "Mapping virtual and physical reality," *ACM Trans. Graph.,* vol. 35, no. 4, pp. 1-12, 2016, Art no. 64, doi: 10.1145/2897824.2925883.

[181] Z.-C. Dong, X.-M. Fu, Z. Yang, and L. Liu, "Redirected Smooth Mappings for Multiuser Real Walking in Virtual Reality," *ACM Trans. Graph.,* vol. 38, no. 5, pp. 1 - 17, 2019, Art no. 149, doi: 10.1145/3345554.

[182] D. Hayashi, K. Fujita, K. Takashima, R. W. Lindeman, and Y. Kitamura, "Redirected Jumping: Imperceptibly Manipulating Jump Motions in Virtual Reality," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 23-27 March 2019, pp. 386-394; doi 10.1109/VR.2019.8797989.

[183] K. Matsumoto, E. Langbehn, T. Narumi, and F. Steinicke, "Detection Thresholds for Vertical Gains in VR and Drone-based Telepresence Systems," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 22-26 March 2020, pp. 101-107; doi 10.1109/VR46266.2020.00028.

[184] Y. H. Cho, D. H. Min, J. S. Huh, S. H. Lee, J. S. Yoon, and I. K. Lee, "Walking Outside the Box: Estimation of Detection Thresholds for Non-Forward Steps," in *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, 27 March-1 April 2021, pp. 448-454; doi: 10.1109/VR50410.2021.00068.

[185] D. Kim, J. e. Shin, J. Lee, and W. Woo, "Adjusting Relative Translation Gains According to Space Size in Redirected Walking for Mixed Reality Mutual Space Generation," in *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, 27 March-1 April 2021, pp. 653-660; doi: 10.1109/VR50410.2021.00091.

[186] J. Zhang, E. Langbehn, D. Krupke, N. Katzakis, and F. Steinicke, "Detection Thresholds for Rotation and Translation Gains in 360° Video-Based Telepresence Systems," *IEEE Transactions on Visualization and Computer Graphics,* vol. 24, no. 4, pp. 1671-1680, 2018, doi: 10.1109/TVCG.2018.2793679.

[187] A. Paludan *et al.*, "Disguising rotational gain for redirected walking in virtual reality: Effect of visual density," in *2016 IEEE Virtual Reality (VR)*, 19-23 March 2016, pp. 259-260; doi: 10.1109/VR.2016.7504752.

[188] P. Gao, K. Matsumoto, T. Narumi, and M. Hirose, "Visual-Auditory Redirection: Multimodal Integration of Incongruent Visual and Auditory Cues for Redirected Walking," in *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, 9-13 Nov. 2020, pp. 639-648; doi: 10.1109/ISMAR50242.2020.00092.

[189] H. Sakono, K. Matsumoto, T. Narumi, and H. Kuzuoka, "Redirected Walking using Continuous Curvature Manipulation," *IEEE Transactions on Visualization and Computer Graphics,* vol. 27, no. 11, pp. 4278-4288, 2021, doi: 10.1109/TVCG.2021.3106501.

[190] B. J. Congdon and A. Steed, "Sensitivity to Rate of Change in Gains Applied by Redirected Walking," in *Proceedings of the 25th ACM Symposium on Virtual Reality Software and Technology*, Parramatta, NSW, Australia, 2019: Association for Computing Machinery, pp. 1 - 9; doi: 10.1145/3359996.3364277.

[191] A. L. Simeone, N. C. Nilsson, A. Zenner, M. Speicher, and F. Daiber, "The Space Bender: Supporting Natural Walking via Overt Manipulation of the Virtual Environment," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 22-26 March 2020, pp. 598-606; doi: 10.1109/VR46266.2020.00082.

[192] D. Reimer, E. Langbehn, H. Kaufmann, and D. Scherzer, "The Influence of Full-Body Representation on Translation and Curvature Gain," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, 22-26 March 2020, pp. 154-159; doi: 10.1109/VRW50115.2020.00032.

[193] S. H. Zhang, C. H. Chen, Z. Fu, Y. Yang, and S. M. Hu, "Adaptive Optimization Algorithm for Resetting Techniques in Obstacle-ridden Environments," *IEEE Transactions on Visualization and Computer Graphics,* 2022, doi: 10.1109/TVCG.2021.3139990.

[194] D. Wolf, K. Rogers, C. Kunder, and E. Rukzio, "JumpVR: Jump-Based Locomotion Augmentation for Virtual Reality," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, Honolulu, HI, USA, 2020: Association for Computing Machinery, pp. 1–12; doi: 10.1145/3313831.3376243.

[195] M. Kim, S. Cho, T. Q. Tran, S. P. Kim, O. Kwon, and J. Han, "Scaled Jump in Gravity-Reduced Virtual Environments," *IEEE Transactions on Visualization and Computer Graphics,* vol. 23, no. 4, pp. 1360-1368, 2017, doi: 10.1109/TVCG.2017.2657139.

[196] Y. J. Li *et al.*, "Detection Thresholds with Joint Horizontal and Vertical Gains in Redirected Jumping," in *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, 27 March-1 April 2021, pp. 95-102; doi: 10.1109/VR50410.2021.00030.

[197] K. Ogawa, K. Fujita, K. Takashima, and Y. Kitamura, "PseudoJumpOn: Jumping onto Steps in Virtual Reality," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 12-16 March 2022, pp. 635-643; doi: 10.1109/VR51125.2022.00084.

[198] V. A. de Jesus Oliveira, L. Nedel, A. Maciel, and L. Brayda, "Anti-Veering Vibrotactile HMD for Assistance of Blind Pedestrians," in *Haptics: Science, Technology, and Applications*, Cham, D. Prattichizzo, H. Shinoda, H. Z. Tan, E. Ruffaldi, and A. Frisoli, Eds., 2018: Springer International Publishing, pp. 500-512.

[199] A. Uematsu *et al.*, "Preferred step frequency minimizes veering during natural human walking," *Neuroscience Letters,* vol. 505, no. 3, pp. 291-293, 2011, doi: 10.1016/j.neulet.2011.10.057.

[200] S. Doyen, O. Klein, C.-L. Pichon, and A. Cleeremans, "Behavioral Priming: It's All in the Mind, but Whose Mind?," *PLOS ONE,* vol. 7, no. 1, p. e29081, 2012, doi: 10.1371/journal.pone.0029081.

[201] A. Liapis, C. Katsanos, M. Xenos, and T. Orphanoudakis, "Effect of Personality Traits on UX Evaluation Metrics: A Study on Usability Issues, Valence-Arousal and Skin Conductance," in *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*, Glasgow, Scotland Uk, 2019: Association for Computing Machinery, p. Paper LBW2721; doi: 10.1145/3290607.3312995.

[202] K. Srinagesh, *The Principles of Experimental Research*, Burlington: Elsevier, 2006. [Online]. ISBN: 9780080497815

[203] J. Lazar, J. H. Feng, and H. Hochheiser, *Research Methods in Human-Computer Interaction*. Cambridge, MA: Morgan Kaufmann (in English), 2017.

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