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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.**

I. 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 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

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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.

II. 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.

A. 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

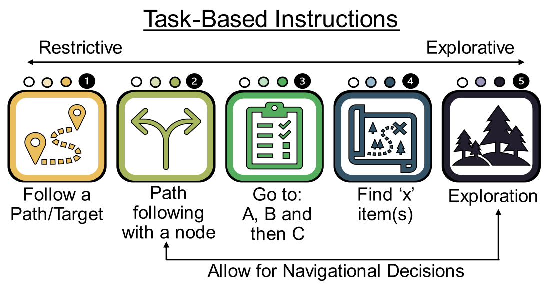

Fig. 1. Navigational Decisions Categorical Scale: ranging from 1-5.

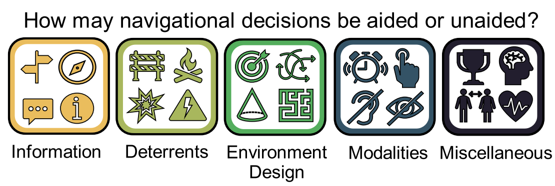

Fig. 2. Aided Wayfinding.

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).

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).

B. *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.

C. *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.

III. 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.

A. *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.

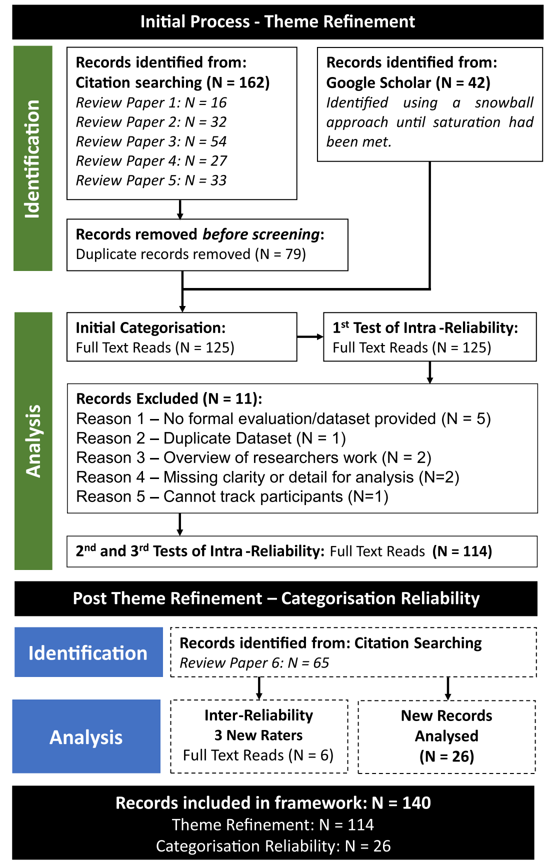

Fig. 3. The overall process (review papers: [6], [8], [9], [10], [11], [14]).

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]. Fig. 3 details the initial identification and retrieval 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.

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 re-analysing 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, available online). 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.

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, $\mathrm{N} = 26$ 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 10$^{\text{th}}$ of March, 2023. Therefore, with both the papers analysed during theme refinement and the categorisation reliability, the final corpus analysed at publication was $\mathrm{N} = 140$ 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 supplementary material, available online). 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.

IV. 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, available online.

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].

A. *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*).

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 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

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, available online.

[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.

B. 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 II.B, 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*'.

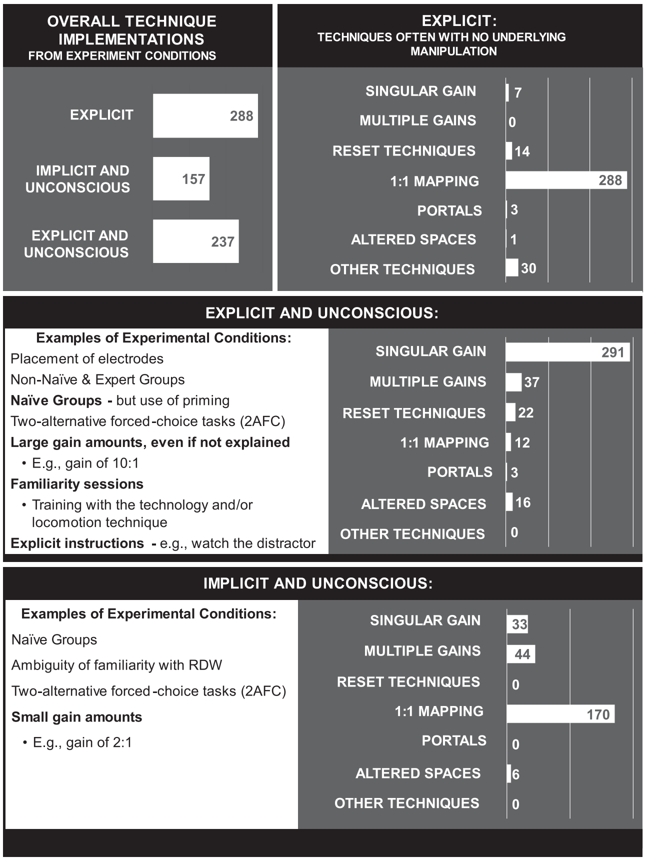

Fig. 6. Short overview of technique implementations regarding noticeability: the total is 977 (experimental conditions). Altered spaces refer to techniques such as flexible spaces, and other techniques refer to techniques such as the magic barrier tape method. Greater detail can be found in the supplementary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

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].

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, available online.

C. 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.

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].

V. 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.

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

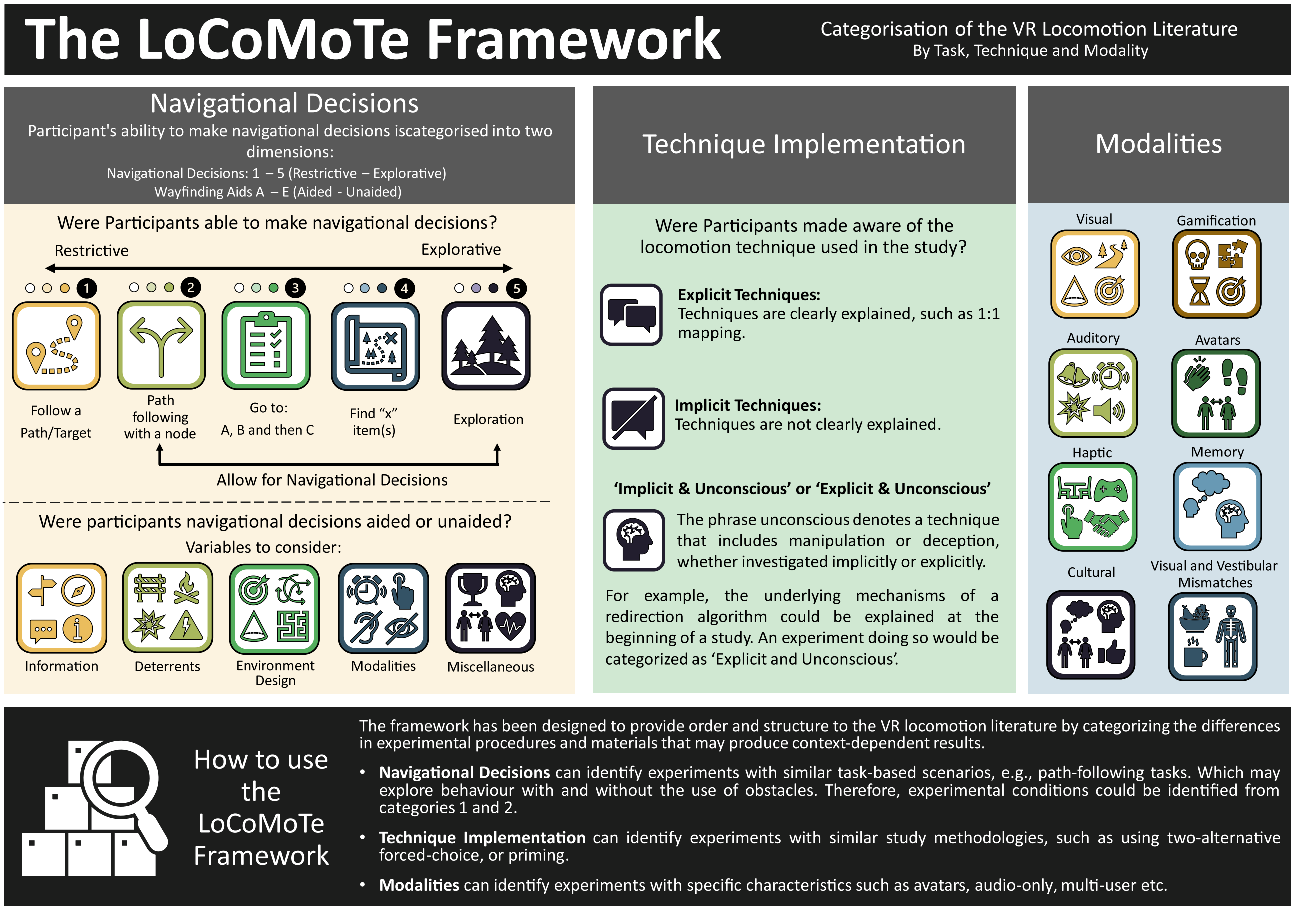

Fig. 8. Summary of the LoCoMoTe framework.

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.

A. 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, available online), 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?"*

VI. 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, available online. 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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