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A Systematic Literature Review of Virtual Reality Locomotion Taxonomies

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Abstract—The change of the user's viewpoint in an immersive virtual environment, called locomotion, is one of the key components in a virtual reality interface. Effects of locomotion, such as simulator sickness or disorientation, depend on the specific design of the locomotion method and can influence the task performance as well as the overall acceptance of the virtual reality system. Thus, it is important that a locomotion method achieves the intended effects. The complexity of this task has increased with the growing number of locomotion methods and design choices in recent years. Locomotion taxonomies are classification schemes that group multiple locomotion methods and can aid in the design and selection of locomotion methods. Like locomotion methods themselves, there exist multiple locomotion taxonomies, each with a different focus and, consequently, a different possible outcome. However, there is little research that focuses on locomotion taxonomies. We performed a systematic literature review to provide an overview of possible locomotion taxonomies and analysis of possible decision criteria such as impact, common elements, and use cases for locomotion taxonomies. We aim to support future research on the design, choice, and evaluation of locomotion taxonomies and thereby support future research on virtual reality locomotion.

Index Terms—Systematic Literatur Review, Survey, Virtual Reality, Immersive Virtual Environments, Locomotion, Travel, Taxonomies, Classification, Semantic Similarity Computation

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1 INTRODUCTION

LOCOMOTION allows users to change their viewpoint in an *immersive virtual environment* (IVE) and is therefore part of most user interfaces for *virtual reality* (VR) systems. A *locomotion method* (LM) realises locomotion in VR and can lead to different advantages and disadvantages such as simulator sickness [1], [2] or disorientation [3]. Over the recent years the number of LMs has risen [4] to meet new requirements, due to new possibilities enabled by technical advances, or because of new insights how LMs affect users. The rising number of LMs presents researchers and designers with a novel challenge: How can LMs and the related knowledge be structured, e.g. to implement VR applications, identify research gaps, or deduce insights from the knowledge gathered by multiple authors?

Several researchers addressed this challenge by proposing a taxonomy, i.e. a knowledge representation [5] in the form of a classification scheme [5], [6] that has a hierarchical structure [5], [7], [8], [9]. Locomotion taxonomies can consist of higher-level locomotion concepts (e.g. *Walking Techniques*) or axes of the design space (e.g. *Input Conditions*). Thus, taxonomies can group locomotion methods or provide a basis to compare them.

Researchers developing a taxonomy have to identify potential use cases which also build the basis for evaluating the taxonomy later on [10], [11], [12], [13], [14], [15]. Currently, there exist several different VR locomotion taxonomies [16]. Thus, researchers who want to use a VR locomotion taxonomy or the contained locomotion concepts in surveys [17], related works [18], or knowledge databases [19] first need to choose one. A well-founded decision requires an overview of all potential choices and a decision basis.

The work of Al Zayer et al. yields a short introduction into 12 VR locomotion taxonomies [16]. Di Luca et al. [19] provide content-wise insights by describing similar nodes of 13 taxonomies. In a previous work we provided potential decision aids for 28 VR locomotion taxonomies based on publication data including the year and impact [20].

However, there exists no systematic content-wise overview and analysis of VR locomotion taxonomies, their evolution, or an identification of possible use cases. Moreover, the amount of identified taxonomies in our previous work suggested that there are taxonomies that have not been considered in existing analyses.

We performed a *systematic literature review* (SLR) of VR locomotion taxonomies including an overview and analysis. Our aim is to support a well-founded choice and the development of new taxonomies based on insights into the research field, providing knowledge from previous work, and by presenting common use cases that enable a user-centred design approach. The insights into the research field focus on presenting where researchers agree and where possible gaps or less explored areas may exist. This is achieved by analysing the agreement among taxonomy authors by extracting common elements and forming clusters of taxonomies. Moreover, interest in the taxonomies from other researchers is considered by means of impact. Since knowledge can change over time, the common elements, the taxonomy clusters and the impact are also considered over time. In addition to providing insights into the evolution of the research field and the knowledge that has already been acquired, use cases can provide the basis for creating, choos-

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ing and evaluating taxonomies in a user-centred approach. Usefulness of taxonomies is one of the most common quality criteria [10] and is often evaluated based on use cases [11], [13], [14], [15]. To support this approach, we have extracted several use cases by extracting the goals described by the authors in the taxonomy publications, which were subsequently fused by several researchers. The identified intentional use cases described by the taxonomy authors can be used for future analyses of actual use cases. Overall, our work provides readers with an overview of existing locomotion concepts, their similarities, and evolution over time as well as common use cases for locomotion taxonomies. Our contributions are the following:

- an overview of existing locomotion elements such as concepts presented by taxonomies and a comparison how they are related,
- a temporal analysis that can be utilised by researchers who are interested in the history of VR locomotion research,
- an identification of common use cases for VR locomotion taxonomies to enable a user-centred design approach and future validation of new taxonomies.

Our contributions are intended to help researchers in the design, choice, and evaluation of VR locomotion taxonomies and concepts and thus drive the research of locomotion in virtual reality. Our SLR shows that researchers can choose between 27 different VR locomotion taxonomies that have been introduced between 1994 and 2020. We extracted three clusters of taxonomies with different elements: decomposition of LMs based on the control elements, grouping of LMs based on the metaphor, and a discrimination between the interaction fidelity or plausibility. The temporal analysis shows a recent trend to the second group of taxonomies and a greater interest in the first group in earlier years. We identified five common use cases by fusing the aims that are described by taxonomy authors. Among the use cases, the exploration of the design space as well as the design and evaluation of LMs were the most frequent ones. Our results suggest that there exist differences in the applicability to some use cases for the identified taxonomy clusters.

Overall, our results show that there are different VR locomotion taxonomy clusters. Within these clusters there is consensus among researchers with respect to the aims of the taxonomy, the use cases, and the common elements while they differ between the taxonomy clusters. In addition, we found that the knowledge and perspectives on knowledge change over time leading to different locomotion taxonomies.

2 BACKGROUND & RELATED WORK

We conducted an initial non-systematic literature review to get an overview of already existing work and background knowledge of VR locomotion taxonomies and taxonomies in general.

Al Zayer et al. list some VR locomotion taxonomies, subdivided into general and specific taxonomies [16]. Di Luca et al. provide an introduction into top-level elements of common VR locomotion taxonomies and later integrate some of them as filter options into their VR locomotion database [19]. However, a systematic literature research or analysis of VR locomotion taxonomies was beyond the scope of both works. In a previous work [20], we performed an analysis of the publication data for VR locomotion taxonomies but did not analyse the taxonomies and their evolution content-wise. Content-wise analyses can provide insights into the knowledge of researchers that is the basis for VR locomotion taxonomies. Kersten-Oertel et al. [21] conduct a content-wise analysis of a mixed reality taxonomy by comparing its components against text corpus statistics.

Other works examine how taxonomies in general can be evaluated. Szopinski et al. [10] performed an SLR of evaluation criteria for taxonomies and found usefulness to be the most frequent one. Nickerson et al. [11] argue that taxonomies should be evaluated with respect to their usefulness, i.e. how well they serve identified use cases or purposes, by including users. The taxonomy evaluation methods identified by Szopinski et al. [13] include case studies where *user experience* (UX) methods are used, illustrative scenarios where the taxonomy is applied and evaluated, e.g. with respect to its completeness or usefulness, and action research where the taxonomies are introduced into the work process to assess their usefulness. Oberländer et al. [14] reviewed several evaluation methods, the most frequent ones were cluster analysis and case study research. Schöbel et al. [15] validate a gamification taxonomy in two use case studies.

Thus, content-wise analyses as well as evaluations with respect to the usefulness based on use cases can help researchers comparing and evaluating VR locomotion taxonomies.

3 RESEARCH QUESTIONS

The state of the art in section 2 served as a basis for formulating our research questions. In addition, the procedure for identifying the research questions involved group discussions among VR researchers. Our goal is a thorough SLR and later analysis of VR locomotion taxonomies to provide an overview and support the choice, creation, and evaluation of locomotion taxonomies.

The basis for a later analysis is the identification of VR locomotion taxonomies leading to the first research question:

R_1: What are existing taxonomies or categorisations for LMs?

Previous works [16], [19], [20] identified different taxonomies where some taxonomies were not identified by other authors and vice versa. This suggests that the identification of taxonomies could be incomplete such that both works do not give a thorough answer to R_1. A reason for this could be that the taxonomies are a means to an end in both works and, consequently, the authors did not conduct a systematic literature review to identify as many taxonomies as possible. Thus, we performed an SLR to identify taxonomies as completely as possible and answer R_1.

Research question R_1 builds the basis for the subsequent analysis of VR locomotion taxonomies to provide content-wise insights. Taxonomies consist of multiple elements that can differ due to different perspectives and estimations which aspects of locomotion are important. Taxonomy elements that have been identified by multiple authors are more likely to be important parts of VR locomotion. Usually, meta-analyses in SLRs fuse different medical studies or user studies with the same research question by deriving a common estimate as answer that is closer to the truth. The meta-analysis approach can be adapted to taxonomies to extract a common estimate of important elements for classifying VR locomotion methods by dense areas of overlap where researchers are in general agreement. Thus, our second research question is:

R_2: What are common elements of these taxonomies?

Common elements are key elements that many researchers identified in their previous works. At the same time, less common elements are part of less explored areas that could be potential research gaps. Thus, researchers get an insight into important elements and research gaps of taxonomies. In addition, we identify clusters of similar taxonomies based on the common elements of the taxonomies. These represent dense areas of overlap where researchers are in general agreement.

Apart from the agreement among authors of a VR locomotion taxonomy, there also exists the interest of the overall community, e.g. researchers applying, adapting, or reviewing the proposed taxonomy. The interest of other researchers in a taxonomy is not considered when regarding the overlap between the taxonomies. This interest shows how much a taxonomy is approved and can therefore be an indication of a useful taxonomy incorporating important key elements. Thus, taxonomies with a higher impact might be interesting when choosing taxonomies, e.g. if the taxonomy is used as a common reference. Therefore, the third research questions considers the impact:

R_3: What impact do these taxonomies have?

So far, our research questions analyse the current state of the research field. However, taxonomies are knowledge representations and knowledge can evolve over time. Novel LMs can be introduced that cannot be assigned to previously considered categories of locomotion, changing the perspective of VR researchers. Disruptive technologies might open new possibilities that have not been considered before. User studies can shift the focus to different categories of LMs. As a result, novel taxonomies are introduced to fill research gaps and cover new trends. Thus, apart from the current state of the research field described by R_2 and R_3, the evolution over time is important to identify possible trends and gaps, i.e.:

R_4: How did the research field of taxonomies evolve?

Research question R_4 involves the impact of taxonomies (R_3) over time as well as the temporal evolution of common elements and taxonomy clusters (R_2). Research questions R_2, R_3, and R_4 help to chose and design taxonomies based on the agreement among taxonomies and their impact. However, less explored areas are not necessarily promising research gaps. Similarities between taxonomies and their impact determine the usefulness of the taxonomies based on the opinions of researchers which do not have to be the users of taxonomies. Thus, a user centred-approach can provide further insights into the usefulness of existing VR locomotion taxonomies as well as reveal gaps that have not been covered yet. In a user-centred approach the context of use, including use case scenarios, is analysed to derive requirements for which solutions are designed and subsequently evaluated. Thus, use cases can enable a user-centred approach for deriving requirements for taxonomies, designing taxonomies, and evaluating taxonomies in future works. This motivated a further research question:

R_U: What are common use cases described by the authors of VR locomotion taxonomies?

Research question R_U focuses on applying an existing taxonomy and omits objectives for designing taxonomies. The use cases are based on the objective the authors describe for applying a VR locomotion taxonomy.

4 METHOD

SLRs can help to reduce bias [22] and enhance the comprehensibility and reproducibility since they are documented. SLRs are frequently used in medicine and most procedures are described for medical research [23], [24], [25], [26]. Kitchenham adapted these procedures for software engineering [26] and the resulting guidelines have been applied in software engineering and, more specifically, in VR research [4], [27], [28], [29]. Thus, we followed Kitchenham's procedure for performing an SLR consisting of three steps: Planning, conducting, and reporting the review [26].

During the planning phase, the need for an SLR is identified and the review protocol is specified. In the following, we describe the review protocol before describing the screening process and results for the identification of articles.

4.1 Search Strategy

The overall research topic of the above research questions and the SLR are VR locomotion taxonomies. Thus, the three main keywords we added to our search strategy were *virtual reality*, *locomotion*, and *taxonomy*. We followed Kitchenham [26] by adding similar terms (e.g. synonyms, abbreviations, or alternative spellings) for each of these keywords to the query keywords. Our preliminary literature review showed that more recent papers tend to use the term *immersive virtual environments*, while earlier works rather use the term *virtual reality*. Thus, we included both terms as synonyms. Next, all query keywords were combined by AND's and OR's to generate the subsequent search strings:

(taxonomy OR classification scheme OR survey) AND
(locomotion OR travel) AND
(virtual reality OR immersive virtual environments)

We executed the queries in multiple search databases: ACM Digital Library [30], CiteSeerX [31], dblp [32], Google Scholar [33], IEEE Xplore [34], Scopus [35], and Semantic

Scholar [36]. Following Badampudi et al. [37], we retrieved the first ten results for each search string. The SLR database queries have been carried out during February and September 2020. In a subsequent step, we performed backward snowballing [38], i.e. we retrieved and screened the publications cited in the primary sources. Since the SLR focuses on the whole history and evolution of taxonomies, there was no restriction to the publication year.

4.2 Study Selection

In group discussion among VR experts, selection criteria were identified and further refined during the study. Papers identified by the search strategy above were narrowed down to relevant publications using selection criteria, i.e. inclusion and exclusion criteria. A directly inflicted exclusion criterion concerned patents since the initial literature review did not yield any patents introducing locomotion taxonomies and their exclusion increases the probability of relevant publications among the first ten search results. Additional criteria selected relevant studies among the retrieved search results. First, duplicates found using different search strings or retrieved from different databases, were omitted. Second, non-English papers were excluded, due to understandability and comparability issues. Third, two researchers screened the remaining publications for an explicit categorisation or taxonomy of LMs in general or of a subcategory of LMs. The first researcher labelled the publications as red, yellow, or green. Publications marked in red most certainly contain no VR locomotion taxonomies, e.g. publications on the travel and holiday industry. Yellow publications were publications in the VR research field and contain a taxonomy or classifications but described them very implicitly. Green publications contained explicit VR locomotion taxonomies. The second researcher was given the evaluation of the first researcher, assessed the labels based on the title, and screened all yellow and green publications for a VR locomotion taxonomy. Subsequently, both researchers discussed the publications and decided by consensus which publications were included. In the last step, reintroductions of taxonomies or taxonomy parts were excluded. Only the first publication of a taxonomy was included. This enabled assessing the impact of taxonomies based on a similar measure: the number of citations of the publication they were first introduced in.

4.3 Study Quality Assessment

Currently, there exists no common procedure to evaluate the quality of locomotion taxonomy papers or the introduced taxonomy. Thus, we did not enforce any quality criteria.

4.4 Data Extraction

The required data is extracted non-automatically from the retrieved publications and Google Scholar. We extracted the full text and reference as well as the following data:

- The proposed taxonomy (addressing R_1, R_2 and R_4)
- The title, authors, publication type (book or book chapter, journal paper, conference paper, or miscellaneous), conference, and year as suggested by Isenberg et al. [39] (addressing R_3 and R_4)
- The number of citations for each year between 1994 and 2021 (addressing R_3)

4.5 Data Synthesis

After extraction, the data had to be synthesised to answer the research questions R_2, R_3, R_4, and R_U which is described in the following. For research question R_1, addressing existing taxonomies, the extracted taxonomies already provide the necessary data.

Common Elements (R_2): We used JSON as a human- and machine-readable standard to collect the data and structure of all identified taxonomies. We have made the JSON file publicly available on Zenodo to enable other researchers an integration into their research projects [40]. We also provide the source text or images from which the taxonomies were extracted to allow an easy traceability of the taxonomy extraction.

Word frequencies can provide a first idea of keywords present among all taxonomies. However, they can have a different spelling or the concept linked to the word might be referred to via synonyms and antonyms. A semantic similarity measure is required to cluster words meaning the same key concept. Common approaches to determine the semantic similarity between two words include computed measures based on databases [41], [42], [43], [44], [45], a text corpus [43], [46], or search engine results [43]. Another option are user studies which yield human similarity measures, e.g. by asking participants for the perceived similarity of words [46], [47], [48].

User studies can be considered as the gold standard [42], [45] but require many participants [46]. This makes user studies especially difficult for VR locomotion taxonomies that might require expert knowledge to assess the semantic similarity of domain-specific concepts. Outcomes between user studies might also differ, resulting in a correlation of up to 0.9 between human similarity measures [45], [46].

Computed similarity measures can have a correlation of 0.65-0.8 against human similarity measures and require less effort [45]. Among the computed similarity measures, using the lexical database WordNet [49], [50] is the defacto standard [41] that is commonly used to semantically annotate benchmark datasets [51]. For small datasets with only few words, there is less variation in the results when different statistical algorithms are used [52]. Since the number of words contained in the taxonomies is small compared with large text corpora, we expect both elaborated and simple statistics to yield similar results. Thus, we use simple statistics on WordNet, a low threshold of 0 distance between at least 3 synsets to prevent wrong semantic clusters, and an additional human estimation of the identified clusters afterwards.

Overall, our method contains the following steps to synthesise the taxonomy data into word clusters, given the JSON-modelled taxonomies:

1) Extract single words from taxonomies by separating at space, slash, and comma signs.
2) Omit simple words (i.e., of, to, and, or, the, a, in, from, yes, no, for), ellipsis and numbers from the analysis.

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3) Cluster step 1 (Misspellings): cluster words that have more than two characters with a Levenshtein distance of up to one.
4) Cluster Step 2 (Alternative Spellings): cluster all different spellings of a word (e.g. walk, walking, walked,...).
5) Manually check for correctness of first two cluster steps.
6) Cluster Step 3 (Semantics): cluster words that are both in at least 3 different synsets in WordNet.
7) Manually check for correctness of third cluster step.

We used WordNet 3.1 and a revised version of Google's WordNet-Blast [53] to access it. We dissolved clusters in step+5 but did not manually cluster words to avoid biased and subjective clusterings. Clusters are also difficult to separate and easier to form ex post by researchers based on the presented results.

In the next step, we identified the word clusters that were used by many authors. For each taxonomy only one occurrence per word cluster was counted to calculate the frequency and the ten most frequent word clusters were extracted.

Taxonomies consist of edges and nodes that contain one or multiple words. In addition to single words, we also aimed to extract similar taxonomy nodes between the taxonomies. For each pair of taxonomy nodes the similarity was computed as the sum of the word similarities between each word of the first node and all words of the second node. We defined the word similarity as one if the two words were in the same word cluster. If this was not the case, we computed the mean synset similarity between each synset of the first word and all synsets of the second word. The synset similarity is based on the shortest path distance (SPD) computed using WordNet-Blast [53]:

$$\text{Synset Similarity} = \frac{1}{(1 + \text{SPD})}.$$

WordNet-Blast traverses the synset tree path for all ancestors common to both synysets and returns the shortest calculated path. We calculated a normalised node similarity measure where the node similarity is divided by the maximum word count of both nodes. For all normalised node similarities from one node to all other nodes, we calculated the z-score based on the normalised similarity measure to one node and the mean and standard deviation of the normalised similarity measures to all other nodes.

Identifying a taxonomy node that is more similar to a node than others equals upper-tailed hypothesis testing. For upper-tailed hypothesis testing, a level of significance of $.001$ equals a z-score of above 3.902. Thus, if node B has a z-score of above 3.902 for a node A it can be considered as more similar to node A than other nodes on a p-value level of $< .001$. To calculate the similarity from one taxonomy to another taxonomy, the score of all similar nodes are added, i.e. all z-score similarities between their nodes that are above 3.902. This sum is divided by the multiplied number of nodes in both taxonomies. If the similarity values differ, we take the minimum of both similarities. To get the z-score values of the taxonomy similarities, the mean and standard deviation from one taxonomy to all other taxonomy are calculated. The z-score similarity between two taxonomies is based on the average mean and average standard deviation of each taxonomies to all other taxonomies. In contrast to the node similarity z-scores where only nodes on a p-level of $.001$ are considered, we analyse taxonomies with similarities on a p-level of $.05$.

Taxonomy Impact ($\mathbf{R}_3$): The number of citations can give an estimation of the impact of the extracted locomotion taxonomies. The overall accumulated number of citations is difficult to compare since it will rise over time. Thus, we observed the number of citations for each year between 1994, where the first taxonomy was introduced, and 2021, which is the last completed year. long papers or books can have a substantially higher number of citations than shorter papers.

Research Field Evolution ($\mathbf{R}_4$): Our analysis with respect to the research field evolution focuses on the impact and common elements. Together, they provide an idea of uprising ideas, elements, and whole taxonomies. In contrast to research questions R_2 and R_3, we focus on the temporal evolution of impact and common elements. To analyse the evolution of the impact, we observe the change in the number of citations during March 2020 and August 2021, yielding an estimation of the recently gained impact. Our analysis of the evolution of common elements consists of computing the top ten common elements for each year, starting with the year where at least three taxonomies had been introduced.

Use Cases ($\mathbf{R}_U$): We extracted text passages where use cases are described and clustered them in common objectives. In a next step, we described the use case in own words and added a title. The use cases were then reviewed and improved in two steps. In the first step, feedback was provided by a researcher with domain-specific knowledge of locomotion taxonomies. In the second step, the use cases where given to a researcher in human-computer interaction without focus on VR.

4.6 Screening Process and Results

In the following, we describe the process of identifying VR locomotion taxonomy articles using the search protocol described in section 4. Figure 1 visualises the described process based on the PRISMA 2020 statement [54].

The queries retrieved 587 publications (ACM Digital Library: 120, CiteSeerX: 119, dblp: 3, Google Scholar: 120, IEEE Xplore: 43, Scopus: 62, and Semantic Scholar: 120). Among these results were 460 duplicates for which the original 132 articles were included while the 328 duplicates were excluded. In addition to the 132 originals, 127 articles without any duplicates were included such that 259 articles remained.

Two papers were written in Korean and Portuguese language and were excluded as well as two papers for which the text was not available and requests to the authors were not answered.

In the next step, 232 articles were excluded since they did not contain a VR locomotion taxonomy or categorisation. The remaining 23 publications contained a VR locomotion taxonomy. Two of the 23 publications reintroduced a VR locomotion taxonomy and were excluded resulting in

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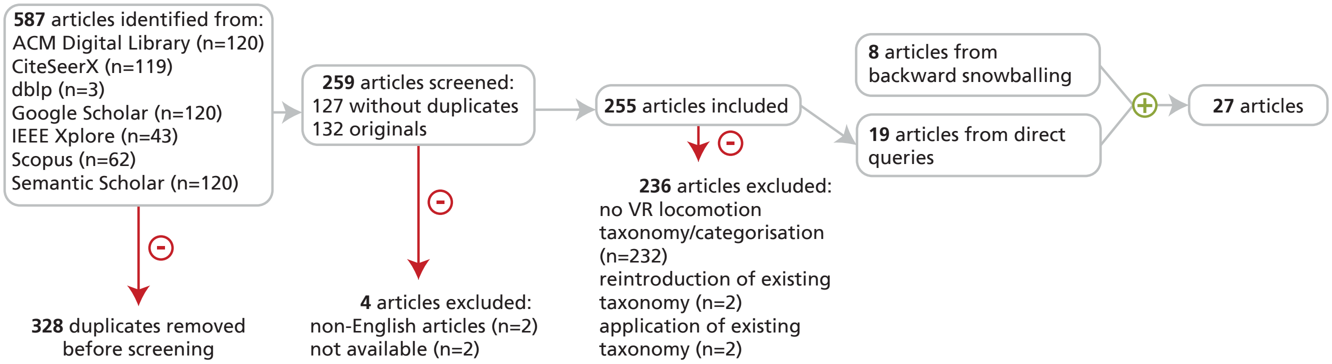

Fig. 1. The study identification and screening process depicted as a flow chart based on the PRISMA 2020 statement [54].

21 publications. Two further taxonomy publications were discarded after a review and discussion of their structure among three researchers. The taxonomy in the publication by Arns and Cruz-Neira [55] merely takes up parts of a taxonomy that was already introduced by Arns [56] in a previous publication. Yi et al. [57] apply the taxonomy by Boletsis [4] and do not propose their own taxonomy.

Some of the remaining 19 publications were retrieved from multiple search databases, resulting in hit rates from 0.83% to 33.33% (ACM Digital Library: 1/120 (0.83%), CiteSeerX: 3/119 (2.52%), dblp: 1/3 (33.33%), Google Scholar: 14/120 (11.67%), IEEE Xplore: 5/43 (11.63%), Scopus: 5/62 (8.07%), and Semantic Scholar: 8/120 (6.67%)). Backward snowballing yielded eight further publications.

Overall, 27 publications were used in our analysis, containing 19 publications found directly via queries and 8 publications found via backward snowballing.

5 RESULTS

In the following, we describe the results of our analysis according to the method described in section 4 for the 27 identified VR locomotion taxonomies. The subsections each address one of the research questions outlined section 3.

5.1 Locomotion Taxonomies

Figure 2–4 depict the extracted VR locomotion taxonomies based on the clusters identified in subsection 5.2 to provide insights of their content and structure. Common elements (see subsection 5.2), are coloured according to Figure 6 to allow the reader an easy localisation and exploration of common elements.

Assessing the scope of the taxonomies based on the root node shows that many taxonomies focus on general aspects of locomotion or travel and fewer taxonomies focus on subgroups of locomotion methods. The root node of most taxonomies was (*Virtual/VR*) *Locomotion/Travel* (*Interfaces/Techniques/Methods*) [4], [56], [59], [61], [64], [65], [66], [67], [68], [69], [70], [71], [72], indicating a more general scope. Bowman et al. implicitly defined this root node in the taxonomy figure caption [72]. The root node of Jerald is called *Viewpoint Control Patterns* [73]. The taxonomy of Tan et al. contained three explicit root nodes named *Task Selection*, *Travel Control*, and *User Interface* [74] and the authors implicitly define the root node *Navigation* in the caption of the figure describing their taxonomy. Other taxonomies focused on general aspects as *Interaction* (*Fidelity*) [75], [76], *User's Movement* [77], or the *Frame of reference* [58].

More specific taxonomies focus on *Through-The-Lens Techniques* [60], *Redirection Techniques* [62], [63], *Walking Interfaces* [78], *Walking Techniques for Incompatible Spaces* [79], *Infinite Walking Solutions* [80], *Walking-based Locomotion Techniques* [81], and *Teleportation* [2].

5.2 Common Elements

According to the method described in section 4, we extracted the ten most common words among all VR locomotion taxonomies.

Common Word Clusters

Due to several elements appearing in the same amount of locomotion taxonomies, our list includes thirteen common elements, all appearing in more than 5 taxonomies. In the following, these are described given associated words in the same word cluster in parenthesis, the frequency, and the reference to the taxonomy publication:

1) **Walk** (Walking, Walking-based), 12, [56], [59], [61], [62], [65], [69], [71], [73], [78], [79], [80], [81]
2) **Technique** (Techniques), 10, [4], [60], [62], [65], [68], [69], [70], [71], [79], [81]
3) **Locomotion**, 10, [4], [56], [59], [61], [65], [67], [68], [71], [76], [81]
4) **User** (User's), 9, [56], [60], [67], [70], [72], [74], [77], [78], [81]
5) **Virtual**, 9, [56], [61], [66], [69], [70], [72], [73], [77], [78]
6) **Travel**, 9, [56], [64], [66], [68], [69], [70], [72], [73], [74]
7) **Move** (Moving, Movement, Motion, Motion-based), 8, [4], [65], [66], [67], [70], [73], [77], [81]
8) **Input**, 7, [2], [56], [64], [67], [72], [74], [81]
9) **Physical**, 6, [4], [56], [66], [68], [72], [77]
10) **Environment** (Environmental), 6, [56], [63], [66], [71], [72], [74]
11) **Steering**, 6, [66], [67], [68], [69], [72], [73]
12) **Continuous**, 6, [4], [56], [63], [66], [72], [74]
13) **Gaze** (Gaze-directed), 6, [56], [66], [69], [72], [73], [77]

While *Locomotion* and *Travel* are often used synonymously in VR, they were not automatically clustered by

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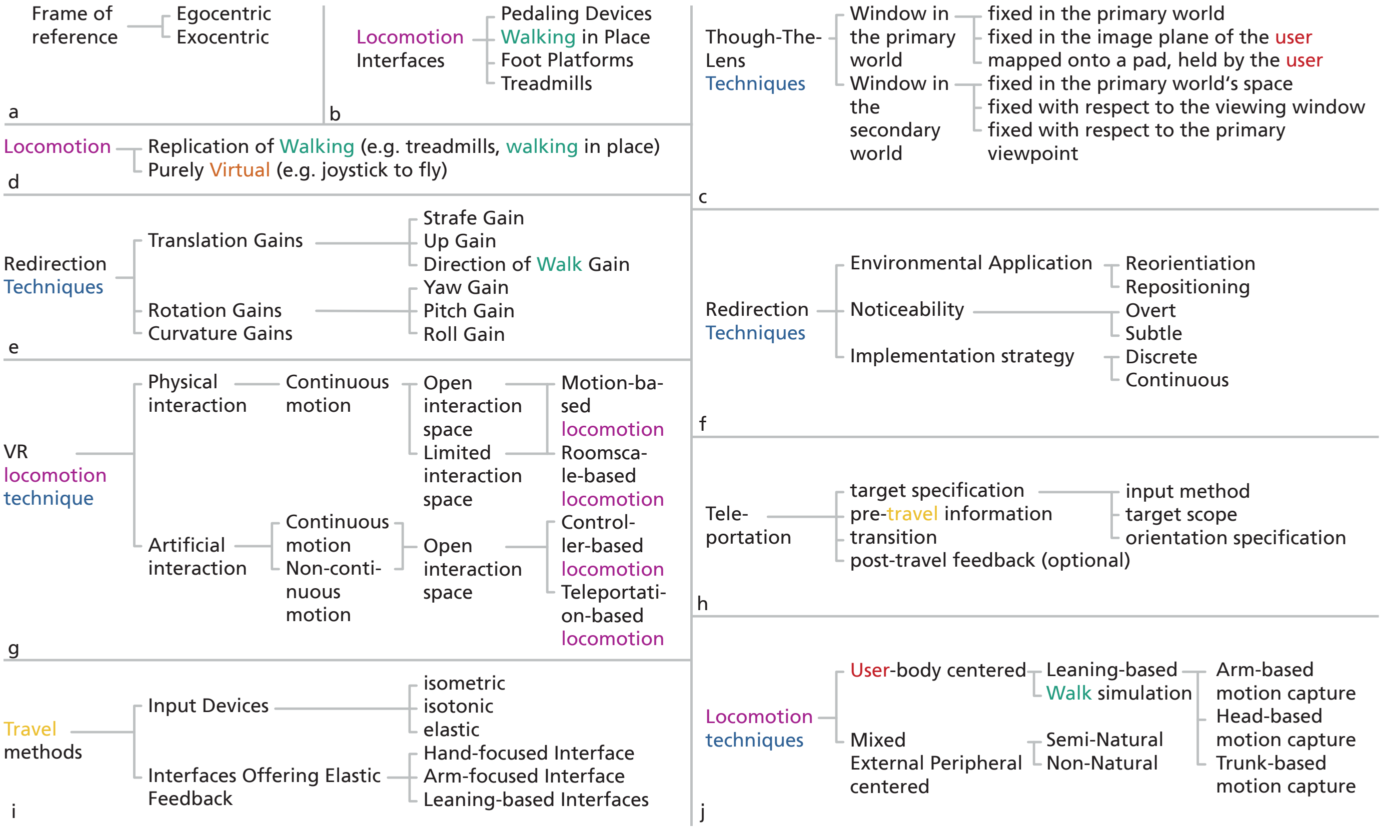

Fig. 2. Non-clustered taxonomies: a) Hand 1997 [58] b) Hollerbach 2002 [59] c) Stoev and Schmalstieg 2002 [60] d) Zanbaka et al. 2005 [61] e) Steinicke et al. 2008 [62] f) Suma et al. 2012 [63] g) Boletsis 2017 [4] h) Weißker et al. 2018 [2] i) Günther et al. 2019 [64] j) Cherni et al. 2020 [65]

WordNet. Overall, 17 taxonomies referenced *Locomotion* or *Travel*. Thus, this cluster would by far exceed the current most frequent element *Walk* that has been referenced in 12 taxonomies. A separated analysis also reveals that most taxonomies either reference the term *Locomotion* or *Travel*. Merely Arns (Figure 3f, [56]) and Bowman et al. (Figure 5a, [68]) use both terms in their taxonomies.

In addition to the most common elements and the taxonomies referencing them, we also extracted the taxonomy nodes that include the identified common elements. Depicting the different taxonomy nodes shows the different perspectives and descriptions that the taxonomies provide on these common elements. Figure 6 shows a word cloud of the taxonomy nodes including concepts that have been referenced by more than eight taxonomies. The size of the cloud elements was chosen according to the number of taxonomies including them as a node. Below the taxonomy node the reference to the taxonomy paper is given. The colour depicts which common element (*Walk*, *Technique*, *Locomotion*, *User*, *Virtual*, or *Travel*) the cloud element includes.

Taxonomy Similarities

In addition to the word clusters, we computed the taxonomy similarities and node similarities which are described in the following.

Overall, three taxonomy pairs had a highly significant similarity score on a p-level of $< .001$ (equalling $z > 3.0902$) and one pair on a p-level of $< .01$ (equalling $z > 2.3263$). Five taxonomy pairs had a significant similarity score ($p < .05$, $z > 1.6449$).

We found the strongest relation between the taxonomies of Arns (Figure 3f, [56]) and Nabiyouni & Bowman (Figure 3g, [81]) with $z = 3.8782$. Both taxonomies have *Rotation* and *Translation* nodes with a similar structure. Translation is related to a *DoF* node with child nodes that list different DoFs. Both taxonomies have a *Position(-based)* node in relation with the *Velocity and Acceleration Selection* or the *Speed* of the *Input* and *Output*. Arns lists *Sliding Sandals* as *Interaction Device* while Nabiyouni and Bowman have *Sliding* as a *Walking Movement Style*. Arns attached a *Body* node as a child of *Physical Rotation*. Nabiyouni and Bowman list different body parts that can be tracked and used as input properties. Nabiyouni and Bowman describe the *Input* and *Input Properties Sensed* and Arns the *Input Conditions*. While Nabiyouni and Bowman designed their taxonomy for *Walking-based Locomotion Techniques* many nodes are similar to Arns taxonomy which describes locomotion in general. Both taxonomies also integrate nodes specifically for walking, e.g. *Walking Surface*, *Scaled Walking*, and *Regular Walking*.

Many of the similarities are due to the integration of the taxonomy by Bowman et al. (Figure 3b, [72]) into Arns taxonomy, which is the second strongest relation ($z = 3.6041$).

We found a strong relation between the taxonomies of Slater and Usoh (Figure 4a, [75]) and Nilsson (Figure 4b, [70]) with $z = 3.1485$. Both taxonomies subdivide the *Interaction* and *Metaphor Plausability*, respectively, into *Mundane* and *Magical*.

Another highly significant similarity was found between the taxonomy of Nabiyouni and Bowman and the taxonomy by Tan et al. (Figure 3e, [74]). Both have a node for *Speed* and

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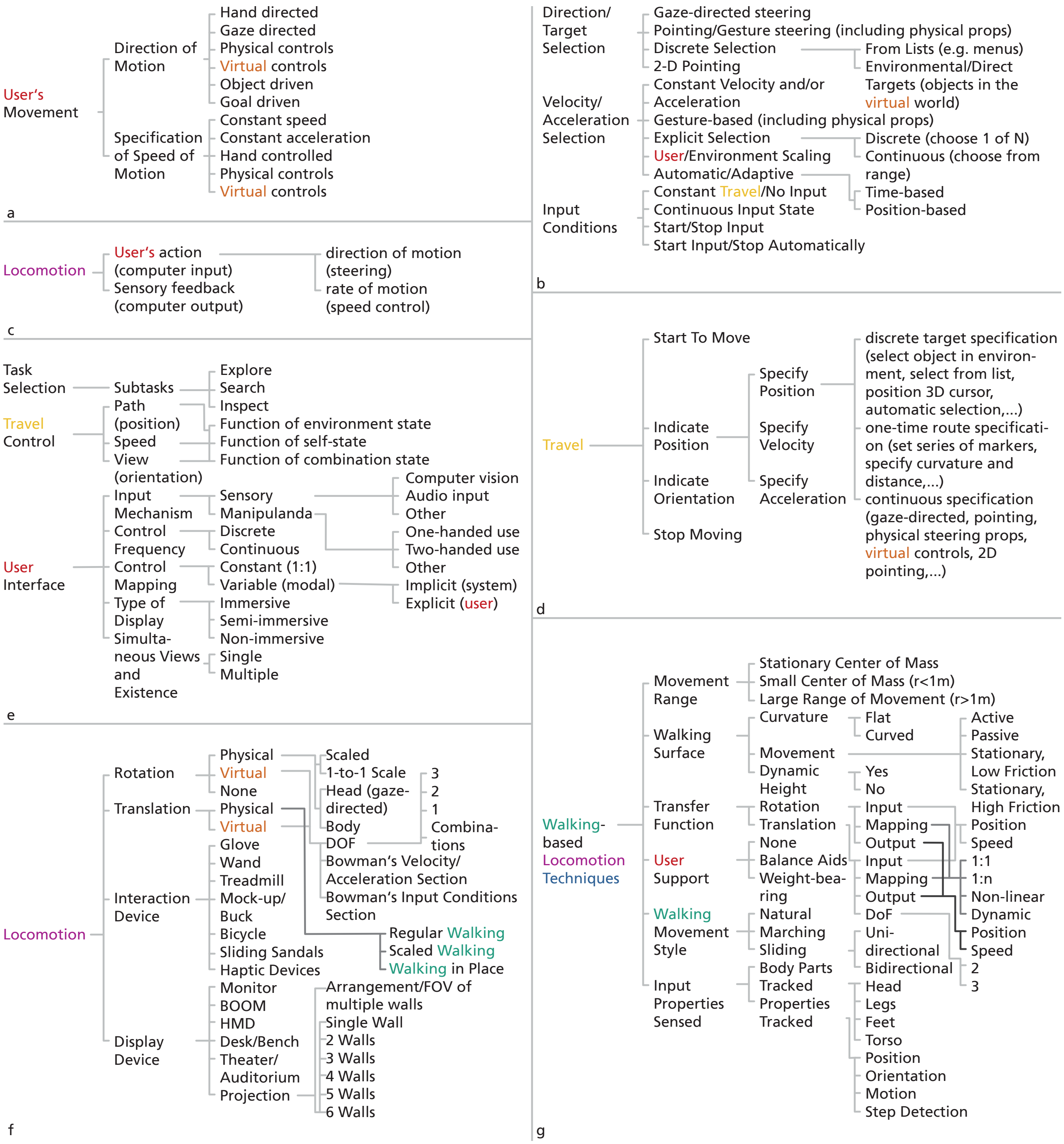

Fig. 3. Cluster 1 taxonomies: a) Mine 1995 [77] b) Bowman et al. 1996 [72] c) Templeman et al. 1999 [67] d) Bowman et al. 1999 [66] e) Tan et al. 2001 [74] f) Arns 2002 [56] g) Nabiyouni and Bowman 2016 [81]

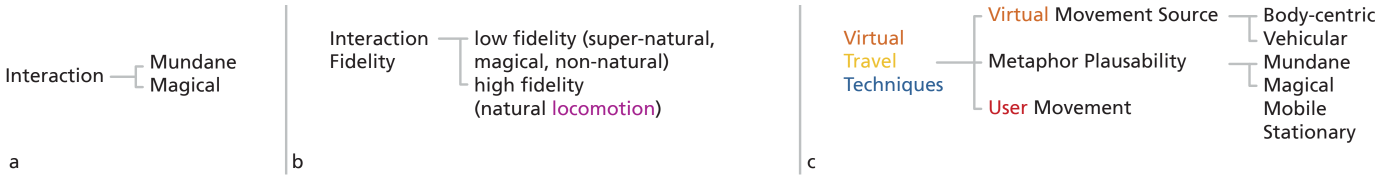

Fig. 4. Cluster 3 taxonomies: a) Slater and Usoh 1994 [75] b) Nilsson 2015 [70] c) Fisher et al. 2017 [76]

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Fig. 5. Cluster 2 taxonomies: a) Bowman et al. 2004 [68] b) Wendt 2010 [78] c) Suma et al. 2010 [69] d) Nilsson et al. 2013 [79] e) Jerald 2015 [73] f) Ferracani et al. 2016 [80] g) Bozgeyikli et al. 2019 [71]

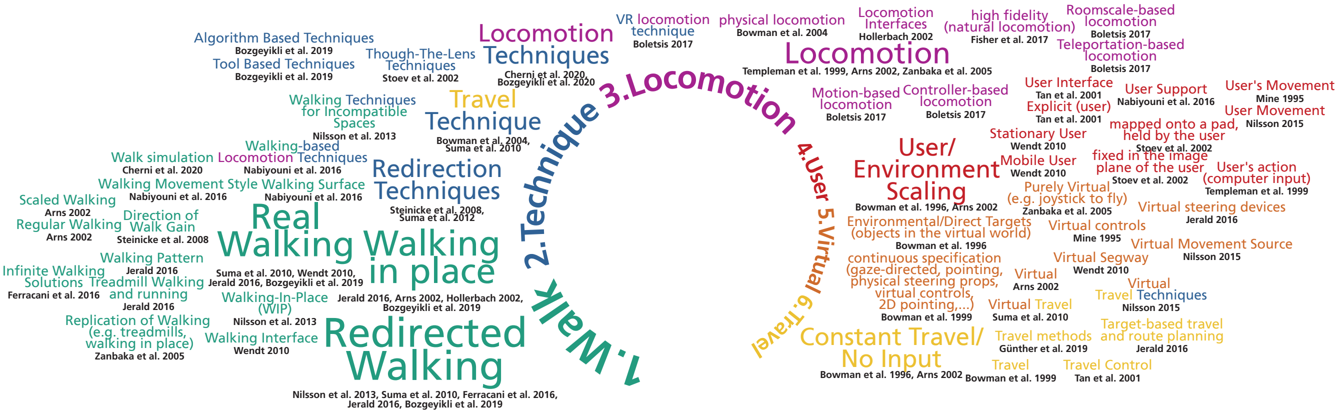

Fig. 6. In the middle, elements referenced by at least nine taxonomies are depicted in descending order, each with a different colour. The taxonomy nodes containing these elements are depicted in the same colour with the reference to the taxonomies below them.

Orientation or *View (Orientation)*. In the taxonomy of Tan et al. they are children of the *Travel Control* while Nabiyouni and Bowman attached *Speed* to the *Input* as well as *Output* and related *Orientation* to the tracked input properties. Both taxonomies have integrate multiple nodes to describe the input: *Input*, *Input Properties Sensed* (Nabiyouni and Bowman) and *Audio Input*, *Input Mechanism* (Tan et al.). In addition both taxonomies contain a node *Mapping* (for the Rotation and Translation) and *Control Mapping* with a child *Constant (1:1)* and *1:1*, respectively.

The taxonomy of Tan et al. is also related to the taxonomy by Arns ($z = 1.9616$). Both have a node for *Discrete* and *Continuous*: Tan et al. integrated them as categories for the *Control Frequency* while Arns integrated the taxonomy part of Bowman et al. where the two nodes are children of the *Explicit Selection* node of the *Velocity/Acceleration Selection*. The discrimination between *Explicit Selection*, *Automatic/Adaptive*, and *Constant Velocity and/or Acceleration* of Arns and Bowman et al. can also be found in the taxonomy of Tan et al. where the *Control Mapping* is divided into the nodes *Constant (1:1)* and *Variable (modal)*, which is again divided into *Explicit (user)* and *Implicit (system)*. Tan et al. distinguish different display types based on the degree of immersion while Arns integrated several *Display Devices* into her taxonomy. While Tan et al. split *Simultaneous Views and Existence* into *Single* and *Multiple*, Arns divided the *Projection* display device into single and multiple walls. Both taxonomies also contain nodes for the input: *Input*

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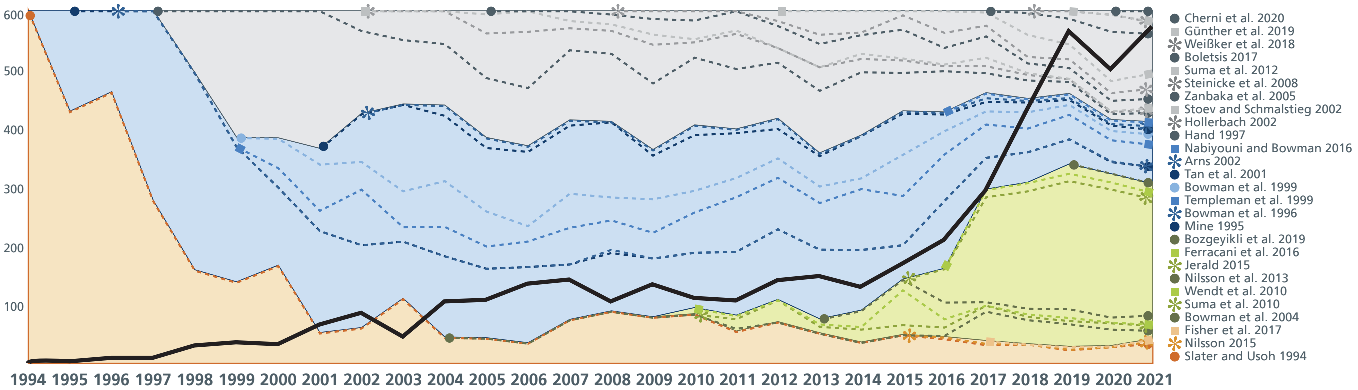

Fig. 7. Percentage of citations per year between 1994 and 2021 for the publications in which the taxonomies where introduced. Unclustered taxonomies are displayed in grey, Cluster 1 taxonomies in blue, Cluster 2 taxonomies in green, and Cluster 3 taxonomies in orange. The black line shows the overall number of citations per year for all introduced taxonomies.

Mechanism and *Audio Input* (Tan et al.) as well as *Input Conditions* (Arns, Bowman et al.).

The third taxonomy related to the one by Tan et al. is Mines taxonomy (Figure 3a, [77]) with z $= 1.6551$ which is mainly due to the frequent use of *control* or *controls*. The taxonomy of Tan et al. contains the nodes *Speed* and *Constant (1:1)* while Mines taxonomy has the nodes *Constant acceleration* and *Constant speed*.

The taxonomies of Jerald (Figure 5e, [73]) and Suma et al. (Figure 5c, [69]) are significantly similar (z $= 1.9349$). Both have a walking section and a steering section. The walking section in the taxonomy of Suma et al. consists of *Real Walking*, *Walking-in-Place* and *Redirected Walking* which can all be found in Jeralds taxonomy under *Walking Pattern*. Suma et al. differentiate *Steering* into *Gaze-directed*, *Pointing-directed* and *Torso-directed*. The first two nodes can also be found in Jeralds taxonomy under *Steering Pattern*.

For a similar reason Jeralds taxonomy can also be related to the one of Bozgeyikli et al. (Figure 5g, [71]) with z $= 1.7186$. The nodes *Real Walking*, *Walking-in-Place* and *Redirected Walking* are also part of the taxonomy by Bozgeyikli et al. as well as the node *Flying/Leaning* which can be related to the nodes *Navigation by leaning*, *One-handed flying*, and *Two-handed flying* in the *Steering Pattern* section of Jeralds taxonomy.

Two significantly related taxonomies are the ones by Fisher et al. (Figure 4e, [76]) and Boletsis (Figure 2g, [4]) with z $= 2.0484$. However, this is due to the use of *locomotion* and *interaction* in both taxonomies und thus can be ignored.

The analysis reveals three clusters where taxonomies are connected by strong similarities within the cluster and non-significant similarities to other taxonomies.

The first cluster consists of the taxonomies (Figure 3) by Mine [77], Bowman et al. [72], Tan et al. [74], Arns [56] and Nabiyouni and Bowman [81] and focuses on the segmentation of a single LM based on the direction/path, speed/velocity/acceleration, position, orientation, input or output.

The second cluster (Figure 5) contains the taxonomies of Jerald [73], Suma et al. [69], and Bozgeyikli et al. [71]. These taxonomies focus on grouping LMs with similar patterns and metaphors especially walking and steering concepts.

The third cluster (Figure 4) consists of the taxonomies of Slater and Usoh [75] and Nilsson [70] which categorise LMs based on the metaphor plausability of the interaction as mundane or magical.

Accumulating the z-values of the clustered taxonomies (z_1, z_2, z_3) for each non-clustered taxonomies reveals tendencies for the three identified clusters. The scope of many taxonomies (Figure 2) differs from the scope of the identified taxonomy clusters ($z_1, z_2, z_3 < 0$), i.e. for Hand [58], Hollerbach [59], Stoev and Schmalstieg [60], Zanbaka et al. [61], Steinicke et al. [62], Suma et al. [63], Boletsis [4], Weißker et al. [2], Günther et al. [64]. The taxonomy by Cherni et al. is undetermined with minor references to the first two clusters ($z_1 = 0.9637, z_2 = 0.5599$).

The taxonomies of Bowman et al. (Figure 3d, [66]) and Templeman et al. (Figure 3d, [67]) can be linked to the first taxonomy cluster with $z_1 = 0.5595$ and $z_1 = 0.1175$, respectively, and $z_2, z_3 < 0$. The taxonomies of Bowman et al. (Figure 5a, [68], $z_2 = 0.8519$, $z_3 < 0$), Wendt (Figure 5b, [78], $z_2 = 4.1184$, $z_3 = 0.5745$), Nilsson et al. (Figure 5d, [79], $z_2 = 1.4918$, $z_3 < 0$) , and Ferracani et al. (Figure 5f, [80], $z_2 = 1.9487$, $z_3 < 0$) are closer to the second taxonomy cluster with $z_1 < 0$. The taxonmy of Fisher et al. (Figure 4c, [76]) differentiates between low fidelity (magical) and high fidelity (natural) interaction and can be placed in the third cluster with $z_3 = 0.3843$ and $z_1, z_2 < 0$.

5.3 Research Field Evolution

To analyse evolution of the research field, the change of impact and common elements as well as the similarities between the taxonomies can show a shifting interest in certain taxonomies and a different focus in the taxonomies itself.

To assess the impact of taxonomies, we retrieved the number of citations for each year between 1994 and 2021 from Google Scholar [33] as described in section 4. Figure 7 shows the proportionate number of citations per year for all taxonomy publications where the colour depicts the taxonomy cluster.

During the first years, approximately until 1998, the work of Mine [77] and especially the work of Slater and Usoh [75] made up the majority of citations. Between 1998–2016, Cluster 1 taxonomies were the most prominent publications followed by a rise of interest in Cluster 2 taxonomies in 2009, that surpass the citation part of Cluster 1 taxonomies in 2017. Since 2017, the book by Jerald [73], which

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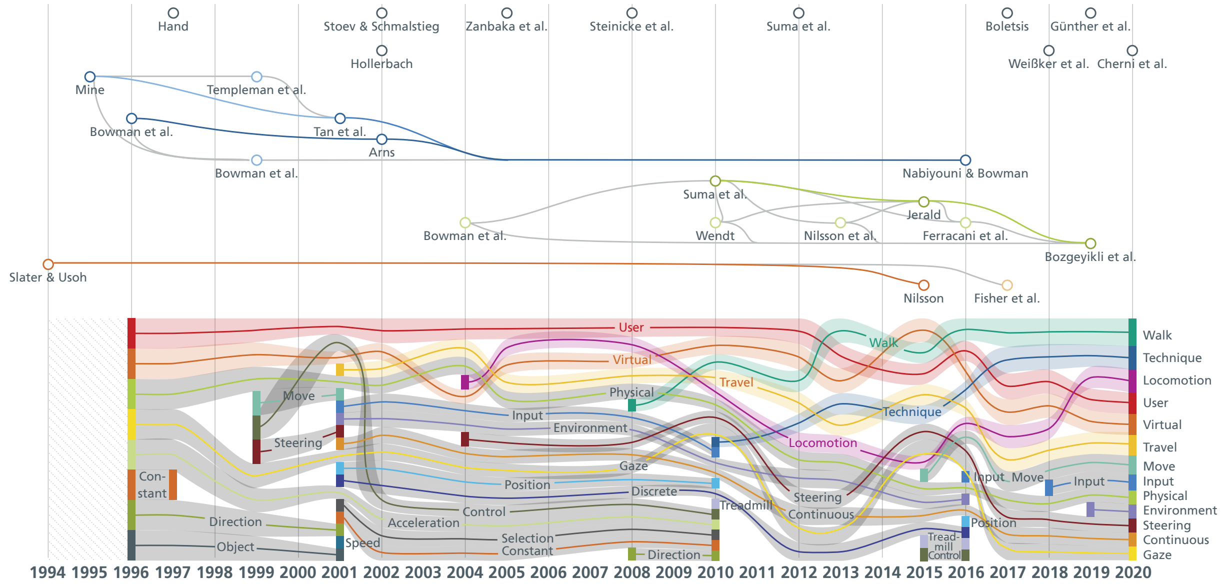

Fig. 8. Temporal depiction of the taxonomies and taxonomy clusters (top) and the common elements (bottom). Top: Edges depict the similarities between the taxonomies and significant similarities if they are coloured. The colour depends on the associated cluster: Unclustered (grey), Cluster 1 (blue), Cluster 2 (green), and Cluster 3 (orange). Blue edges are darker for a higher p-value level of significance. Bottom: For each year the top ten common elements are shown. More elements per year are displayed, if there are equally ranked elements for the 10th place. For each year the common elements are sorted in descending order by the number of taxonomies it was referenced by. The thickness of the lines is proportional to the number of taxonomies referencing the element. The top 6 elements also displayed in Figure 6 have a coloured background, while all other elements have a gray background.

introduced a Cluster 2 taxonomy, has the greatest part of all citations. Unclustered taxonomies made up a substantial part of the number of citations until 1998. A major part can be related to the work of Hand [58] and later to the work of Boletsis [4] that had the second highest number of citations in 2021 after Jerald [73].

Figure 8 shows a temporal depiction of the VR locomotion taxonomies, with the clusters identified in subsection 5.2 together with the change of the ten most common elements since 1996. In the following, we examine the temporal evolution of the taxonomy clusters and their impact on common words in VR locomotion taxonomies.

The first taxonomy cluster, depicted in blue in Figure 8, starts with the taxonomy by Mine in 1995 and ends with the taxonomy by Nabiyouni and Bowman in 2016. However, Cluster 1 can rather be placed in the period from 1995 to 2002, since all taxonomies but the last one have been published in this time period. The same holds for the second cluster in green where all taxonomies but the one by Bowman et al. in 2004 have been published in the time period from 2010 to 2019. The third cluster in orange consists of the taxonomies by Slater and Usoh in 1994, by Nilsson in 2015, and by Fisher et al. in 2017.

The taxonomies of the Cluster 1 shape the period from 1995 to 2010 and classify LMs based on the way different *Control* elements (Common Element in Figure 8: 1999–2010, 2015–2016; Mine 1995, Bowman et al. 1999, Templeman et al. 1999, Tan et al. 2001) have been chosen, i.e. how the *Input* (2001–2010, 2016; Bowman et al. 1996, Templeman et al. 1999, Tan et al 2001., Arns 2002, Nabiyouni and Bowman 2016) has been designed. Many contain a discrimination based on the specification of the *Direction* (1996-2001, 2008–2010; Mine 1995, Bowman et al. 1996, Templeman et al. 1999) and *Position* (2001–2010, 2016; Bowman et al. 1996, Bowman et al. 1999, Tan et al. 2001, Arns 2002, Nabiyouni and Bowman 2016). Another part of most of the taxonomies in Cluster 1 is the *Acceleration* (1996–2010; Mine 1995, Bowman et al. 1996, Bowman et al. 1999, Arns 2002), *Speed* (2001; Mine 1995, Templeman et al. 1999, Tan et al. 2001, Nabiyouni and Bowman 2016) and/or *Velocity* (Bowman et al. 1996, Bowman et al. 1999, Arns 2002). Another key element was the *Constant* (1996–1997, 2001–2010; Mine 1995, Bowman et al. 1996, Tan et al. 2001, Arns 2002) travel, acceleration, speed/velocity, and/or control frequency.

The taxonomies of Cluster 2 shape the period from 2010 to 2020 when elements that were often used in taxonomies of Cluster 1, e.g. the input, direction or acceleration, were discarded in favour of grouping LMs based on common metaphors or design patterns. The foundation was laid by Arns in 2002 with the first integration of a walking category and Bowman et al. in 2004 where the focus was a discrimination merely based on metaphor, e.g. as steering and target-based, or type of *Technique* (2010–2020; Bowman et al. 2004, Suma et al. 2010, Bozgeyikli et al. 2019). Taxonomies in Cluster 2 integrated different *Walking* methods (2008–2020; Suma et al. 2010, Wendt 2010, Nilsson et al. 2013, Jerald 2015, Ferracani et al. 2016, Bozgeyikli et al. 2019), e.g. via a *Treadmill* (2010, 2015-2016; Wendt 2010, Jerald 2015). The most common ones are *Redirected Walking*, *Walking in place*, and *Real Walking* (see Figure 6). The second most common category are *Steering* methods (1999–2001, 2004–2020; Bowman et al. 2004, Suma et al. 2010, Jerald 2015).

The third cluster contains taxonomies which categories LMs as mundane or natural and magical. While this categorisation was first introduced in 1994 by Slater and Usoh, it has not been adapted over two decades. Only two more recent taxonomies embedded such a categorisation: The one by Nilsson in 2015 and the one by Fisher et al. in 2017. Thus, a mundane/magical discrimination is not reflected in the common words depicted in Figure 8.

5.4 Use Cases for VR Locomotion Taxonomies

The previously described results provide data of the taxonomies and publications itself. One of the follow-up questions that arose from these results concerned the motivation and intention for VR locomotion taxonomies and how they can be applied. To answer this question, we derived use cases based on the method described in section 4.

Overall, we extracted five use cases in which VR locomotion taxonomies can be applied and depicted them in Figure 9. The use cases were ordered based on how a process with a locomotion method or component could look like. First one explores the design space. Subsequently, one either finds an existing method or component, or if none of the existing ones satisfies the requirements one creates a new method or component. Afterwards, this locomotion method or component is evaluated and the taxonomy can be used as a common reference to transfer its design and idea.

This process is similar to parts of the user-centred design process according to the ISO 9241-210 standard [82] where a design solution is created first, e.g. by exploring the design space and finding or creating a locomotion method or component, before evaluating it.

We found that most authors described exploring the design space and evaluating locomotion methods or their components as a use case for VR locomotion taxonomies, followed by the use case of creating a locomotion method or component, finding a locomotion method or component, and using the taxonomy as a common reference.

The exploration of the design space was identified by authors introducing a Cluster 1 taxonomy, i.e. Mine [77], Bowman et al. [66], Tan et al. [74], and Nabiyouni and Bowman [81], Jerald [73] who introduces a Cluster 2 taxonomy, and Boletsis [4] who introduces a non-clustered taxonomy. Design spaces consist of multiple dimensions which represent the design possibilities and potential choices [83], [84]. The design space can be defined in a systematic approach by identifying similarities and differences of multiple existing designs to define the dimensions of the design space [83], [84]. These identified design spaces can be useful for design space exploration where multiple designs or design options are compared by designers with respect to the given requirements [83]. Cluster 2 taxonomies focus on describing components of LMs and possible design choices instead of clusters of LMs, i.e. they ”partition the design space” [66]. Thus, they are designed to allow an exploration of the design space. Mine and Bowman et al. argue that their Cluster 2 taxonomies provide ”a good understanding of the types of interaction that are possible” [77] and help to ”understand the space of possible techniques” [66] by decomposing it into ”smaller, more easily understandable pieces” [66]. Nabiyouni and Bowman point out that this decomposition and identification of design space parts enables users to ”analyze the components of [...] locomotion techniques”. Tan et al. explicitly state that their taxonomy is meant to ”drive the exploration of the design space” [74]. In contrast, the taxonomy of Jerald does not decompose LMs and thus does not contain different dimensions of the design space. Instead, it identifies groups of LMs and allows the user to ”identify possible design choices”, i.e. discard or further examine whole groups of LMs. Boletsis' [4] approach for defining a taxonomy is equivalent to the process of defining a design space: in an SLR existing design solutions, i.e. LMs, are identified and subsequently analysed and compared to ”map the VR locomotion research field [and] identify research gaps in the field that warrant further exploration”. During the analysis different design space dimensions are identified and integrated into the taxonomy. Zielasko et al. [85] provide an example for this use case by using the taxonomy of Suma et al. [63] for their design space exploration.

Four authors suggested that taxonomies can help finding an already existing locomotion method or component [56], [66], [73], [81] by helping with the choice [66], [81]. In order to make a well-funded choice one needs a given set of requirements as well as an overview of all possible choices to prevent skipping a possible solution that could have fulfilled the requirements better than all considered solutions. A taxonomy can provide such an overview by describing ”types of locomotion available” [56]. Jerald suggest that taxonomies can also help when searching for alternatives ”when a specific technique fails” [73] since users can then consider ”other techniques within the same pattern” [73]. In the same way taxonomies can help to choose a component [66], [81].

A related use case is the creation of a locomotion method or component [56], [66], [67], [74], [81]. By separating LMs into their components, locomotion taxonomies allow a more modular workflow where single components can be replaced [56] or multiple components can be combined [56], [81]. Other authors point out that taxonomies can guide [56], [66] and inspire [74] during the creation process. Nabiyouni [86] provides an example for creating a novel locomotion method based on a taxonomy.

The evaluation of an LM or its components was described by six authors as an application for VR locomotion taxonomies [2], [56], [66], [71], [73], [81]. The suggested ways that taxonomies could support evaluations range from helping with the planning of the experiment [66], over supporting comparisons [2], [56], [73] to making the results more understandable [81]. Arns [56] and Bowman et al. [66] propose to use their taxonomies as a ”framework”. Bowman et al. [66] further specify that, in addition to the taxonomy, performance metrics and outside factors are also part of the framework. In this framework taxonomies can help to ”generate ideas for experimental evaluation” [66] by ”[d]esigning experiments that vary particular components systematically and independently”. In addition, locomotion methods can be compared to each other [56], [73] by classifying them using a taxonomy which reveals similarities and differences [56]. When evaluating LMs, different results can be attributed to the identified differences which helps to ”understand the effects of design choices” [81]. An example of this use case is the user study by Dewez et al. [87] where the taxonomy by Boletsis [4] was used to choose the locomotion methods evaluated in the use study.

A less frequently described use case is to use taxonomies as a common, standardised description [4] or a ”common reference” [66]. This supports the communication between

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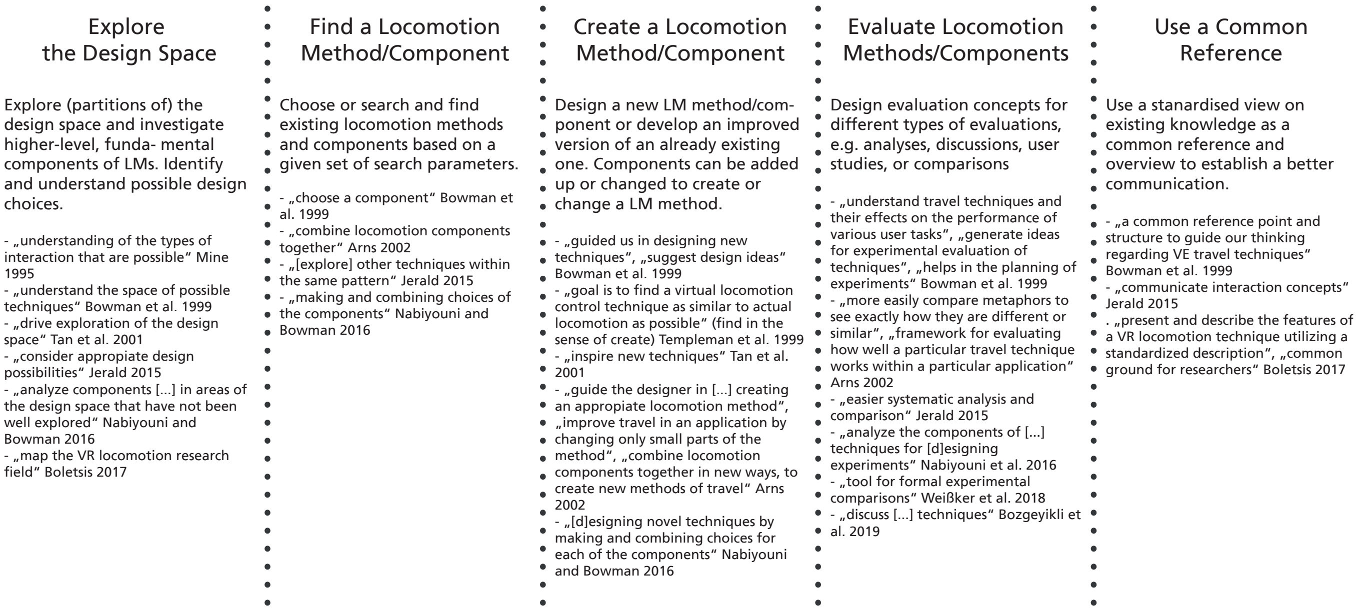

Explore the Design Space	Find a Locomotion Method/Component	Create a Locomotion Method/Component	Evaluate Locomotion Methods/Components	Use a Common Reference
Explore (partitions of) the design space and investigate higher-level, funda- mental components of LMs. Identify and understand possible design choices.	Choose or search and find existing locomotion methods and components based on a given set of search parameters.	Design a new LM method/component or develop an improved version of an already existing one. Components can be added up or changed to create or change a LM method.	Design evaluation concepts for different types of evaluations, e.g. analyses, discussions, user studies, or comparisons	Use a stanardised view on existing knowledge as a common reference and overview to establish a better communication.
- „understanding of the types of interaction that are possible“ Mine 1995 - „understand the space of possible techniques“ Bowman et al. 1999 - „drive exploration of the design space“ Tan et al. 2001 - „consider appropiate design possibilities“ Jerald 2015 - „analyze components [...] in areas of the design space that have not been well explored“ Nabiyouni and Bowman 2016 - „map the VR locomotion research field“ Boletsis 2017	- „choose a component“ Bowman et al. 1999 - „combine locomotion components together“ Arns 2002 - „[explore] other techniques within the same pattern“ Jerald 2015 - „making and combining choices of the components“ Nabiyouni and Bowman 2016	- „guided us in designing new techniques“, „suggest design ideas“ Bowman et al. 1999 - „goal is to find a virtual locomotion control technique as similar to actual locomotion as possible“ (find in the sense of create) Templeman et al. 1999 - „inspire new techniques“ Tan et al. 2001 - „guide the designer in [...] creating an appropiate locomotion method“, „improve travel in an application by changing only small parts of the method“, „combine locomotion components together in new ways, to create new methods of travel“ Arns 2002 - „[d]esigning novel techniques by making and combining choices for each of the components“ Nabiyouni and Bowman 2016	- „understand travel techniques and their effects on the performance of various user tasks“, „generate ideas for experimental evaluation of techniques“, „helps in the planning of experiments“ Bowman et al. 1999 - „more easily compare metaphors to see exactly how they are different or similar“, „framework for evaluating how well a particular travel technique works within a particular application“ Arns 2002 - „easier systematic analysis and comparison“ Jerald 2015 - „analyze the components of [...] techniques for [d]esigning experiments“ Nabiyouni et al. 2016 - „tool for formal experimental comparisons“ Weißker et al. 2018 - „discuss [...] techniques“ Bozgeyikli et al. 2019	- „a common reference point and structure to guide our thinking regarding VE travel techniques“ Bowman et al. 1999 - „communicate interaction concepts“ Jerald 2015 . „present and describe the features of a VR locomotion technique utilizing a standardized description“, „common ground for researchers“ Boletsis 2017

Fig. 9. Identified use cases for applying VR locomotion taxonomies with the title, description and citations of mentions in the taxonomy publications.

researchers [4], [73] by using "broader pattern names and concepts" [73], such as *Flying*. Communication on a more abstract level conveys the rough idea without giving a more time-consuming description that clearly distinguishes one technique from another" [4]. A taxonomy can be especially helpful for "interaction aspects and functionalities that were previously difficult to describe" [4]. For example, Martinez et al. [17] use the taxonomy by Bowman et al. [68] to structure their systematic review and Di Luca et al. [19] use taxonomy elements for their VR locomotion online database called LocomotionVault.

6 DISCUSSION

To address R_1 (What are existing taxonomies or categorisations for LMs?), we retrieved 27 VR locomotion taxonomies that have been introduced between 1995 and 2020. The overlap between the taxonomies identified in previous works of Al Zayer et al. [16], Di Luca et al. [19], and our previous work [20] shows the difficulty of identifying and extracting locomotion taxonomies. Smaller overlaps can be due to different methods, foci, and different understandings of what a taxonomy is. We retrieved 12/12 (100%) of the taxonomies found by Al Zayer et al., and 11/14 (79%) of the taxonomies found by Di Luca et al. (see section 5). The three works included in the analysis by Di Luca et al. were not included in our analysis and most likely not found since they describe locomotion methods instead of categories [88], [89], [90]. We discarded two of the taxonomies included in our previous work because one was a slightly altered re-introduction and one applied an already existing taxonomy. Al Zayer et al. found 12 of our 27 taxonomies (44%), but at least four were published after their publication (12/23, 52%). Di Luca et al. found 8 of the 27 taxonomies we analysed (30%). The comparison to previous work shows that we found 79%-100% of the locomotion taxonomies detected previously suggesting that we provide a thorough answer to R_1.

To answer research question R_2 (What are common elements of these taxonomies?), we identified common elements among all taxonomies but also common elements that were predominantly found in clusters of taxonomies. Some common elements over all taxonomies identified by us were too general to provide much insight, e.g. Locomotion, while others, e.g. Input, were predominantly used by specific clusters of taxonomies. Some of the identified common elements overlap with the one's identified by Di Luca et al. (Walking, Move/Motion, Input, Continuous). Other elements identified by Di Luca et al. do not occur in our list of common elements, e.g. the discrimination between egocentric and exocentric have only been used by Hand et al. [58]. We found that some of the identified elements of Di Luca et al. were frequently used in Cluster 1 taxonomies but are less common when regarding all taxonomies (Control, Velocity/Speed, Acceleration, Direction). As our results show, taxonomies are not homogeneous but form groups with unique common elements and a different focus, e.g. grouping or decomposing LMs. Thus, it is more meaningful to extract common elements for taxonomy clusters and there is not a single answer to R_2 but rather multiple answers for each cluster of taxonomies. Our analysis revealed three clusters of taxonomies: Cluster 1 taxonomies focused on the decomposition of LMs, Cluster 2 taxonomies grouped LMs based on the metaphor, and Cluster 3 taxonomies separated concepts between Mundane/Natural and Magical. The elements Speed/Velocity, Acceleration, Selection, Constant and Object are used exclusively by Cluster 1 taxonomies. Position, Control, and Direction are used mainly by Cluster 1 taxonomies. Cluster 2 taxonomies often contained elements related to Technique, Walking, and Steering. The focus on walking and steering suggests that other metaphors such as teleportation are currently underrepresented and could be considered more closely. Taxonomies in Cluster 3 all contain the elements Mundane or Natural and Magical.

Our analysis of the citation data (R_3: What impact do

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these taxonomies have?) estimates how the impact evolves over time. We found that recently the interest in taxonomies in general increased but also shifted from decomposing taxonomies to metaphor-based taxonomies. Our results are based on the citation data and merely estimate the impact since higher citation numbers can be due to multiple reason. However, our results are consistent with previous work. This is in line with our previous work where we found a similar rise of interest in 2015 based on a rising number of taxonomies that have been introduced.

Our results for research question R_4 (How did the research field of taxonomies evolve?) suggest that the knowledge that taxonomies model evolves over time. Decomposing taxonomies have been mostly introduced during 1995 and 2002 while metaphor-based taxonomies have been a more recent trend. With the introduction of new taxonomies, the importance of common elements that are present in all taxonomies can increase or decrease. In our previous work we also found a shift to more specific taxonomies instead of taxonomies for locomotion in general. This change in VR locomotion taxonomies can be due to novel knowledge or a changing understanding of the knowledge. Di Luca et al. pointed out that knowledge changes over time and proposed a database for locomotion methods that evolves over time, i.e. enables users to add novel locomotion methods. To provide a further ability to adapt to the changing knowledge, the underlying knowledge model, i.e. the taxonomy, should be also capable to change over time.

To answer research question R_U (What are common use cases described by the authors of VR locomotion taxonomies?), we identified five use cases. The use cases we present can be used in a user-centred approach to design novel taxonomies but also to evaluate existing taxonomies as proposed in several related works [11], [13], [14], [15]. We found that some use cases were only described for specific taxonomy clusters. The use case of creating a method based on components was only described for decomposing Cluster 1 taxonomies. The authors of Cluster 2 taxonomies mainly described the use case to explore the design space and to use the taxonomy as a common reference. Thus, our results can help to identify which use cases might be applicable to a given taxonomy. The rising interest in metaphor-based taxonomies could lead to an increased interest in associated use cases as exploring the design space and using a common reference. With a growing design space and accumulating existing knowledge due to the rising amount of locomotion methods over the recent years [4], the importance of these use cases can increase.

7 CONCLUSION & FUTURE WORK

Locomotion is part of most virtual reality applications and over the recent years the amount of knowledge on VR locomotion has risen. While knowledge representations such as taxonomies can help to structure this knowledge and many VR locomotion taxonomies have been introduced, there exists no survey and in-depth analysis of VR locomotion taxonomies. We performed an SLR to retrieve VR locomotion taxonomies and further analysed them by

- visualising their structure and outlining their scope (R_1)
- extracting common elements, similarities and clusters of taxonomies that are similar (R_2)
- comparing their impact based on citation data (R_3)
- analysing the temporal evolution of common elements together with the temporal evolution of taxonomy clusters (R_4), and
- extracting common use cases (R_U)

Our work provides researchers, developers and designers with a visual overview and analysis of current VR locomotion taxonomies and the locomotion concepts contained within them. The locomotion concepts within taxonomies support several use cases, including the common use cases we identified and described.

Our SLR provides a systematic overview of locomotion taxonomies and concepts as well as insights into gaps, such as little emphasis on teleportation, and emerging trends, as the increasing focus on groups of LMs based on metaphors instead of splitting LMs into components. Our analysis supports the decision for locomotion concepts or whole taxonomies, e.g. when structuring locomotion knowledge or communicating locomotion methods. Researchers and designers can use these insights to create novel locomotion methods, e.g. by using metaphor-based design approaches or focusing on less explored areas as teleportation.

The temporal analysis of VR locomotion elements shows how locomotion concepts evolved over time and can be used by researchers interested in the history of VR locomotion. Together with other temporal depictions such as the introduction of locomotion methods [19] it can provide additional insights into the temporal evolution of the research field.

The identified use cases support a user-centred taxonomy design and can be utilised later on to evaluate the created taxonomy. We found that the structure, focus and interest in taxonomies changes over time and suggest to enable future taxonomies to adapt and evolve. The use cases also enable researchers to evaluate and compare multiple locomotion concepts such as metaphors with respect to their usefulness for the identified use cases.

Our work provides insights into how researchers aim to structure the rising knowledge in VR locomotion research and what their main objectives are. We hope to inspire and drive future work in the area of VR locomotion and the structuring of VR locomotion knowledge.

Future work could focus on an extension of the use cases by use cases described in other research areas, as, e.g., using taxonomies for learning and teaching [91]. Since our analysis of citation data merely estimates the impact of taxonomies, further insights into the impact of VR locomotion taxonomies are required. This could be achieved by analysing how taxonomies have been applied and what the results were, e.g. user studies and novel locomotion methods. This analysis could also provide interesting examples for the identified use cases and taxonomy preferences for specific use cases. Additionally, we are interested in evaluating how well already introduced taxonomies perform for the identified use cases to provide a decision basis based on use cases for researchers applying locomotion taxonomies. The integration of VR locomotion taxonomies into typical workflows as the user-centred design process [92] as suggested by Schweiß et al. for an AR taxonomy [93] could further motivate the usage of locomotion taxonomies. We are interested in how taxonomies could change over time to adapt to a changing knowledge or shifting interest.

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Titles are written in bold for publications included into our analysis.

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