Systematic Literature Review on User Logging in Virtual Reality

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ABSTRACT

In this systematic literature review, we study the role of user logging in virtual reality research. By categorizing literature according to data collection methods and identifying reasons for data collection, we aim to find out how popular user logging is in virtual reality research. In addition, we identify publications with detailed descriptions about logging solutions.

Our results suggest that virtual reality logging solutions are relatively seldom described in detail despite that many studies gather data by body tracking. Most of the papers gather data to witness something about a novel functionality or to compare different technologies without discussing logging details. The results can be used for scoping future virtual reality research.

CCS CONCEPTS

• **Computing methodologies** → **Virtual reality**; • **General and reference** → *General literature*;

KEYWORDS

Systematic Literature Review, User Logging

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1 INTRODUCTION

Virtual reality (VR) has gained attention in the recent years because of the popularity of consumer affordable equipment. This has also increased interest in VR research and various kinds of user studies with data collection in VR has been conducted. The reasons for data collection varies from getting evidence about the functionality of a novel VR solution to analyzing users. User logging enables a way to do user analytics but it is difficult to say how popular it is in VR research. Related questions include what kind of systems are built for logging the data and how they are described in the literature.

In this systematic literature review, we study the role of user logging in VR research from software engineering perspective. We are especially interested in the following research questions:

- RQ1: How VR user logging appears in VR research?
- RQ2: How data collection has been made in VR research?
- RQ3: For which reasons the logging or data collection has been made in VR research?

First, we mapped the reviewed papers to the four VR data collection groups suggested by Steptoe et al. [79]: *body tracking* (kinesic behavior, verbal signals, proxemics), *questionnaires and interviews* (subjective sense and experience), *performance metrics* (action quantification) and *physiological response* (stimuli experienced in VR).

Then, we categorized the papers according to the reason of data collection. From the papers' content, we distilled the five following categories: "getting evidence about functionality", "how users act in application usage domain", "comparing VR-aided and non-aided", "comparison of different VR implementations" and "logging development".

After the categorization, we studied closely the papers that describe developing user logging systems in VR. It turned out that there are relatively few papers discussing the topic in detail even though we tried to include papers broadly rather than strictly so that we would not miss anything relevant. In addition to the detailed papers, there are a few papers briefly discussing topics such as logging features, log files, collaborative or distributed data collection, log analysis, and log visualization.

From the 638 papers found with the search terms, we included 78 papers for the final review. The outcome of this study can be used for getting insight on what VR research has been focused on, and for scoping future research. For example, our study suggests that body tracking is the most popular data collection method and there is a minority in studies collecting physiological data from VR users. In addition, the majority of the studies gather user data for getting functional evidence about a new VR solution. Still, our observations suggest that VR logging solutions are relatively seldom explicitly discussed even if some kind of (body) tracking is used in the study.

2 BACKGROUND

VR can be defined as "a real or simulated environment in which a perceiver experiences telepresence" [80]. VR often requires a use of special set of hardware, for example a head-mounted display (HMD). This special equipment in turn often includes a body tracking sensors and features so that VR environment can respond to user activities such as head movement. Via these sensors, it is possible to receive data about the user. Those data can be logged so that it is possible to do analysis based on the logs.

In general, software users have been tracked for various reasons. For example, in human-computer interaction work it can be used for getting statistics about the detailed use of the system, and it can be used after the release or during user testing [35]. Runtime traces have been analyzed for improving architecture, performance, design

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and usability [74]. Multiple authors [8, 16, 62] discuss tracking and analyzing users in web.

VR developers have similar needs and reasons to log users. For example, Ritchie et al. [73] discuss the benefits of user logging within VR in the following way: it is an almost non-intrusive method of capturing a rich data source for analysis, it minimizes user interactions during the data capture, it has potential to reduce time overhead of the capturing process, and the captured data can also be reused. They also note that for achieving the full benefits of VR logging, capturing methods need to be researched. Our study contributes to identifying the capturing methods in need for more research.

Augmented reality (AR) and mixed reality (MR) are closely related concepts to VR and some logging techniques used for AR and MR can be applicable for VR as well. AR is something that combines real and virtual, is interactive in real time, and is registered in three dimensions [2]. MR is a broader term that combines AR and augmented virtuality [61]. While 360-degree videos are on the edge of being VR, we are also working with 360-degree videos and wanted to include papers from that domain. 360-degree videos are omnidirectional videos where user can control the direction of viewport in a spherical space and the controlling often happens with special equipment such as HMD. Similarities in logging 360-degree video users and VR users are related to logging information about head orientation and gaze direction. However, in 360-degree videos users seldom have a possibility to change location in the space, while there can be a user interface and user interactions similar to VR.

We have developed a user logging and visualization framework for 360-degree videos and we are interested in how our solution fits with the related research. On the other hand, we have a broader interest in what VR researchers need and use logging for, and we would like to see how popular is logging in relation to other data collection methods such as interviews. By conducting a systematic literature review, we aim to get insight on the role of logging in VR research.

We are not aware of other systematic reviews concentrating on user logging or data collection in VR systems. Still, VR related systematic reviews exist. For example, Santos et al. [19] identified usage of requirements engineering in development of VR systems which is related to our work in a sense that it has also a software engineering context. Berntsen et al. [5] present another systematic review where VR systems have been categorized to three categories according to their use: *health*, *exploration*, and *presentation and entertaiment*. For example, their *exploration* category overlaps partly with our *usage domain* category.

While it is not a systematic review, Zhao [93] surveyed VR domain and suggests different classifications for VR systems. For example, classification by system functions divides VR systems in three categories: *training & drill*, *planning & design*, and *presentation & entertainment* whereas classification by data flow makes four categories: *platform data* (metadata produced by computer system, network, etc.), *model data* (world, 3D scenes, etc.), *sense data* (output offered to user), and *control data* (input by users). We did not think that those classifications are useful to us as such, but we are mainly interested in the last aforementioned *control data*.

Furthermore, user logging appears in systematic reviews outside VR domain. For example, a systematic literature review by

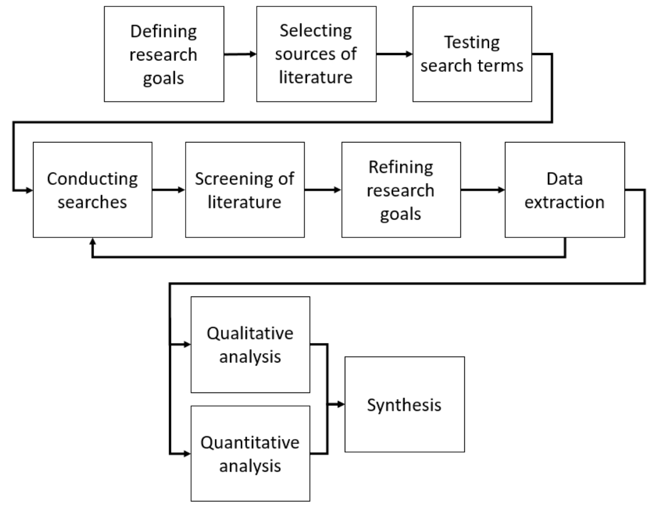

Figure 1: Flow of the review process.

Velsen et al. [82] found that questionnaires seem to be the most popular method, followed by interviews and data log analysis in user-centered evaluation studies.

3 REVIEW PROCESS

3.1 Planning

We created the search terms based on our RQs. VR is a bit difficult search term because VR can relate to immersive or non-immersive VR where immersion refers to illusion of being physically present in a simulated world [26]. We were mainly interested about immersive VR but included also papers about non-immersive VR. AR and MR are closely related concepts so we included them in our search terms since a logging system for them can be relevant to VR research as well.

- VR logging
- AR logging
- virtual reality logging
- augmented reality logging
- HMD logging
- head mounted display logging
- helmet mounted display logging
- mixed reality logging
- head orientation logging
- head orientation tracking

Figure 1 visualizes the flow used in the study. First, we defined preliminary research goals that were just to get an idea of popularity and role of logging in VR. Then we chose our electronic databases IEEE Xplore and ACM Digital Library because those are often used in the field of information technology. Testing of the search terms could have been a more accurate process, but we tested a few terms to see that we receive at least some relevant results. Testing the search terms was a bit problematic because we refined the research goals later. Before conducting the final searches, we created inclusion and exclusion criteria. The research was conducted during late 2017 and early 2018.

3.2 Inclusion and Exclusion Criteria

We aimed to get a large number of studies to get a fuller representation of the available research rather than a focused small number of studies that, on the other hand, could improve the quality of the papers. We tried to find HMD related logging but if it was not explicitly stated, other VR related data collection such as mobile or wearable devices was also allowed. It was not always easy to see if the paper used logging, so we tried to accept papers openly. We accepted papers starting from year 2000. The reason was that we think HMD based VR has progressed after 1990s and we thought that VR logging analytics does not have a long history before 2000. The search results did not include many papers done before 2000 so only few papers were not included because of the publishing year.

We excluded the paper if VR, AR, MR or 360-degree videos was not mentioned. In addition, some kind of data collection was required so, for example, the paper should not only describe a new technology without data collection. As an exception, a paper explicitly discussing logging development was not required to include data collection.

3.3 Identification

We executed the searches by starring with IEEE Xplore and then continued with ACM Digital Library. We used the default search field of both the database websites.

Table 1. Selection process of the literature.

Source	*All*	*Abstract*	*Year*	*Content*	*Included*
IEEE	328	74	72	37	37
ACM	310	94	90	41	41
Total	638	170	164	78	78

Table 1 summarizes the effect of inclusion and exclusion criteria on the amount of papers on different phases. Column *All* shows the full amount of found papers. The column is problematic in a sense that we only checked the 50 first results from the queries that produced hundreds of results. We did this because we discovered that the relevance decreases often fast after the first ten results. Column *Abstract* shows the amount of promising papers accepted after reading title and abstract. It can be seen that most of the papers were excluded at this point. Column *Year* shows the papers accepted by year.

We made data extraction after almost every single search and not only after all of the searches had been conducted. This is presented in Figure 1 with an arrow from *Data extraction* to *Conducting searches*. This gave us a possibility to make small adjustments to the research goals, data extraction form, and inclusion criteria during the searches.

3.4 Data Analysis

Since we had papers that include similar and comparable content, we had material for a quantitative analysis. On the other hand, since we were interested about the reasons for data collection, we had to identify those reasons as well. Thus, we distilled five categories according to the reason of data collection by reading the papers and categorized the papers to those groups. The five groups were:

(1) Papers that collected data to prove something about a novel technique or a product they have studied or developed.
(2) Papers that studied how users act in a certain domain, for example, in a museum.
(3) Papers that compared users' activities with and without VR gear.
(4) Papers that compared different technologies.
(5) Papers that explicitly discussed or studied VR logging.

Qualitative aspect of the analysis comes from the effort of identifying those categories and finding the role of logging. The papers discussing about logging solutions from technical point of view were not always comparable to those concentrating on user studies.

4 RESULTS

Table 2. Amount of publications per year.

Year	*ACM*	*IEEE*	*Total*
2000	0	1	1
2001	0	2	2
2002	0	0	0
2003	0	1	1
2004	1	0	1
2005	0	1	1
2006	2	1	3
2007	0	3	3
2008	0	2	2
2009	2	0	2
2010	1	0	1
2011	1	0	1
2012	2	4	6
2013	2	3	6
2014	5	1	6
2015	5	5	10
2016	10	7	18
2017	10	6	17

The amount of included publications per year can be seen in Table 2. It can be seen that the amount of related research has increased during the recent years. Figures 2 and 3 visualize our analysis results. One paper could fit to multiple categories which explains why the sum of papers in Figure 2 is bigger than *Total* in Table 1.

In Figure 2, the data collection categorization (body tracking, performance metrics, physiological response, and questionnaires and interviews) is based on suggestion by Steptoe and Steed [79]. It can be seen that body tracking was the most popular method. We included everything that collected data by tracking kinesics, verbal signals, oculesics or proxemics into this category. For example, usage of HMD as a data collection tool was categorized in this group. Table 3 lists the publication references.

Body tracking was the most used data collection method (49%) and it was more used in papers found from IEEE Xplore when compared to ACM Digital Library. Performance metrics was the second in the amount of papers (42%), also a few more found from in IEEE Xplore. In this category, we included papers that measured

Table 3. Included papers categorized by data collection method and source.

Source	*Body tracking*	*Perf. metrics*	*Physiol. response*	*Quest. and interv.*
IEEE	[21–23, 25, 28, 32, 34, 39, 42, 46, 55–57, 60, 66, 69–71, 73, 76, 79, 81, 91, 92]	[4, 9, 10, 23, 28, 41, 42, 44, 45, 55, 56, 60, 65, 66, 69, 75, 85, 91]	[17, 79]	[3, 13, 21, 44, 50, 55, 60, 69, 75, 92]
ACM	[7, 11, 14, 18, 20, 27, 29, 52, 53, 63, 68, 78, 84, 87]	[1, 15, 29, 38, 40, 47, 49, 51, 53, 54, 72, 78, 86, 88, 89]	-	[1, 6, 12, 15, 18, 24, 30, 31, 33, 36, 37, 48, 53, 58, 59, 64, 67, 68, 72, 77, 78, 83]

Table 4. Included papers categorized by reason for data collection and source.

Source	*Func. evidence*	*Usage domain*	*VR vs. non-VR*	*Tech. comp.*	*Logging devel.*
IEEE	[9, 13, 22, 32, 39, 41, 42, 45, 46, 55, 57, 70, 71, 76, 81]	[56, 73]	[3, 10, 17, 28, 85, 91]	[21, 34, 44, 50, 60, 69, 75, 92]	[4, 25, 65, 73, 79]
ACM	[1, 11, 14, 15, 24, 29, 31, 36, 54, 58, 59, 63, 64, 67]	[37, 40, 51, 66]	[6, 12, 20, 38, 49, 72, 77]	[7, 18, 27, 30, 33, 47, 48, 51, 53, 54, 68, 78, 84, 87–89]	[52]

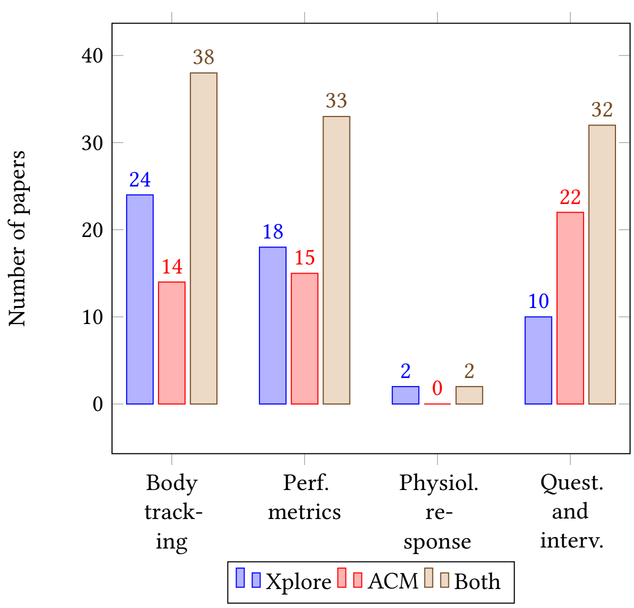

Figure 2. Categorization according to data collection method. The categories are body tracking, performance metrics, physiological response, and questionnaires and interviews.

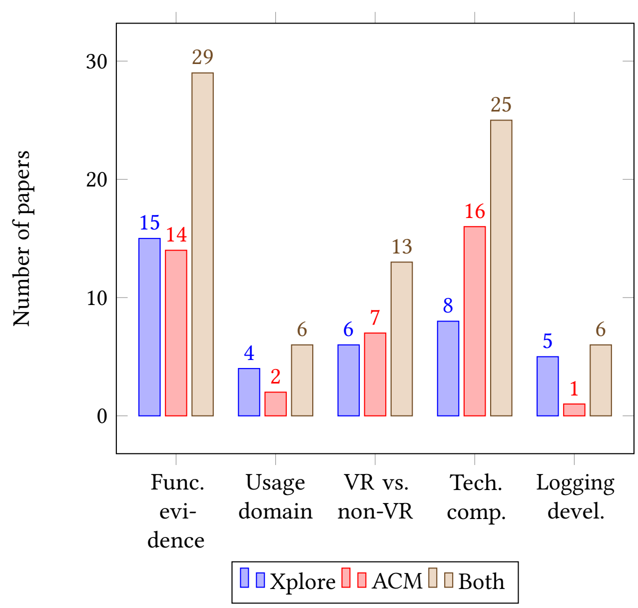

Figure 3. Categorization according to reason for data collection. The categories are getting functional evidence, collecting data in usage domain, comparing VR-aided and non-VR-aided, comparing technologies, and Logging development.

how users performed certain actions in the VR. For example, these papers measured how fast a test subject finished a certain operation in VR or how many times a test subject used certain interaction methods in VR.

The third biggest category (41%), questionnaires and interviews, was chosen if the paper mentioned using either of the methods. It was often relatively clear to see if the paper used this method. This category was more often found from ACM Digital Library and it was the only category where ACM Digital Library had a bigger set of papers when compared to IEEE Xplore.

Physiological response was chosen when the study measured phenomena like heart rate or blinking. Some papers studied physiological phenomena, for example cybersickness [83], using questionnaires but they were categorized to interviews and questionnaires group. We identified zero papers from ACM Digital Library and two papers (3%) from IEEE Xplore to this category [17, 79].

Figure 3 shows the classification to five categories according to the reason of data collection distilled from the papers' content. *Func. evidence* refers to getting evidence about the functionality of a VR solution, *Usage domain* refers to getting data about how users act in the application domain, *VR vs. non-VR* refers to comparisons between VR-aided and non-VR-aided usage, *Tech. comp.* refers to comparisons between different technology solutions, and *Logging devel.* refers to activities such as log analysis, log specification and log replay. One exception that did not fit to any of these categories was a paper about experiencing fun in VR despite cybersickness [83]. It could have been in a category called *Other* or *VR experience.* Table 4 lists the paper references according to reason for data collection.

Func. evidence is the most popular reason (37%) and it almost equally appeared in papers from both the sources. It was followed (32%) by *Tech. comp.* where ACM had more (21%) papers than IEEE (10%). The category *VR vs. non-VR* had almost equal amount of papers from both the sources (8% and 9%) and the total amount is clearly less when compared to the two biggest categories. *Logging devel.* shares the least amount of total papers (8%) with *Usage domain.*

Thus, the remaining six papers (8%) were categorized to *Logging devel.* group where we aimed to classify the papers focusing on logging. In those papers, the logged data was used for:

- Evaluating a logging format [73, 79]
- Analysing logs [25, 52, 73]
- Replaying VR events [4, 73]
- Log management [65]

To elaborate on the paper's content a bit more, Steptoe et al. [79] present a general multimodal data capture and analysis architecture that aims in log standardization. Ritchie et al. [73] demonstrate the potential of VR CAD tool logging by using an XML based log file and automated log analysis. Lo et al. [52] visually analyze head orientation of 360-degree video viewers and published an open head tracking dataset. Fitzgerald et al. [25] give a description of their body logging system with a motion storage and visual analysis. Belfore [4] describes a Java application using Virtual Reality Modeling Language which allows logging and restoration of VR sessions. Nakamura et al. [65] propose an AR behavior log management technique in which real world locations and objects are tagged with virtual cubes.

5 DISCUSSION

5.1 Role of Logging in VR Research

While we identified only six papers with logging as their primary topic, many other papers discussed logging aspects so that logging was not the main idea of the paper. We found the following topics to be discussed:

- Logging features or log files: [3, 9, 22, 34, 38, 39, 41, 48, 55, 60, 76, 81, 85, 87, 91].
- Collaborative or distributed data collection: [10, 28, 32, 46, 66, 68].
- Log analysis and visualization: [7, 20, 21, 23, 27, 45, 53, 56, 57, 70, 71, 88, 92].

Naturally, some kind of technical solution is needed for logging. Examples for such include: relational database [48], a multi-purpose logging module [9], Unity 3D tool [91], and logging server [46].

Orientation, position and time are common log entries in this domain. So, for example, Euler angles [39], rotational position and time [87], gyroscope, accelerometer, gaze [68], and magnetometer [55] have been logged. Less usual, and more domain specific, log data includes text entries [60], conversation [81], user's performance [25], trajectories [91], interactions [3], context [38], and activities [66].

Logging is a method for studying collaboration. It has been used, for example, for studying pair work in a combat simulator [10], interactive television event [28], humanoid robots' behavior [46], and general MR collaboration [68]. Despite that, the described logging architectures are more often local and focused on getting functional evidence about a single solution instead of being distributed platforms for long-term log analysis.

The eventual benefits of logging come from the log analysis. Examples of visual analysis include graphs, charts, plots [7, 20, 27, 45, 57], maps, trajectories and heat maps [23, 56, 70, 92], playback, and timelines [71]. An example of statistical analysis is game players' performance analysis [21].

When identifying the role of user logging in VR research, we came to conclusion that logging (only) head orientation and logging analysis are not very common (22%) [7, 20, 21, 27, 34, 44, 48, 53, 55, 60, 69–71, 76, 87, 88, 92]. Instead, many studies are interested in logging other wearable devices or sensors. Some of the logging is made without specific devices just by tracking the user's activities in virtual environment. The log can be also based on video motion capture.

Using body tracking equipment does not mean that the tracking information is explicitly logged or that the log is analyzed. Furthermore, logging details are not always outspoken even if rest of the VR system is explained in detail. However, if a study uses body tracking as a data collection method, explicit logging is more likely to be used.

While we accepted publications about 360-degree videos, only a few papers discussed them (for example [18, 24, 52, 55]). We could have found more by including them explicitly in the search terms.

5.2 Validity

Logging can be more popular than our results suggest – sometimes there is challenge to identify research that only tracks the user from research that also uses the tracking logs as research data by reading the paper.

One weakness in the study is that the review was completely done by one researcher. Guidelines for systematic reviews suggest that some decisions would be better to do with a support of another researcher to reduce the researcher bias [43].

The categorization by data collection method (Table 3) can be considered unbalanced and, as such, not well motivated. However, for other categories than physiological response it is relatively balanced, and it clearly shows that physiological response is not well represented in the past research. We expect this category to get more popular in the future since cybersickess has gained more attention recently.

Bookkeeping about duplicate papers found with the search terms was not thorough. For IEEE Xplore, this information was included more accurately but for ACM not every duplicate was marked especially in a situation when the query results only provided duplicates. However, the results do not include duplicate papers and we even excluded too similar papers (same authors, same topic, etc.) to reduce bias.

Snowballing is an alternative strategy to do a systematic review [90]. Snowballing to both directions together with the database searches could improve the validity and introduce more interesting papers.

Quality aspects of the included studies were not considered in depth. For the most cases, we required some kind of data collection, but for example, we could have assessed the study design to ensure a minimum level of quality [43]. On the other hand, then we could have had less material.

We used the default search field of the electronic libraries. The results could have been more accurate if we had used the advanced search options. For example, we could have used advanced search with Boolean expressions. Furthermore, we could have found more relevant papers with more and improved search terms. For example cave automatic virtual environment (CAVE) could have been included while our personal interests are on HMDs.

We chose year 2000 or later in our inclusion criteria. It is possible that there are relevant papers done before that. However, the VR technology evolves so that we think that studies that are more recent are more relevant. In addition, we think that there has been a relatively lot of VR research recently (after 2010) which can be also seen in our Table 2. In addition, there might be some studies published in 2017 that had not been yet added to the databases when we executed the queries.

One goal of a systematic review is to present a repeatable research process. Replication of this study is supported describing the process together with the inclusion and exclusion criteria. We assume that there are additional relevant publications available but our searches did not found them. However, we think that 78 papers is a representative amount of papers on which relatively valid conclusions can be made.

6 CONCLUSION

In this systematic literature review, we studied how user logging has been discussed in VR research. While identifying the role of logging, we categorized research papers according to data collection method and the reason for data collection.

Our observations suggest that publications about logging development in VR are relatively rare and logging details are not usually discussed even if logging has been made. The data collection categorization suggests that measuring physiological response is rare when compared to other data collection methods (body tracking, performance metrics and questionnaires and interviews). The categorization according to reason for data collection suggests that the most popular reasons for collecting data are to get functional evidence about a novel VR technology or comparing different VR technologies with each other.

According to this review, VR user logging development calls for more research, generalization and common practices. One way to improve the situation could be to encourage the VR researchers who log users to discuss the used logging procedure more in detail.

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