

Mixed Methods Designs for User Studies in Cross Reality

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ABSTRACT

Mixed methods methodology is a research approach that combines qualitative and quantitative data collection and analysis. This allows to synthesise both types of data for answering the complex research questions posed in cross reality research. However, all research methods have benefits and drawbacks as well as methodological backgrounds. Therefore, we first discuss the underlying foundations of qualitative, quantitative and mixed methods methodology, before looking into how these approaches are applied in cross reality research. Therefore, we selected exemplary published work for each of the methodologies and discuss the research design, as well as limitations and benefits of the used methodologies. After this discussion of real cross reality research designs, we summarise further considerations for the practical application of mixed methods research designs.

Index Terms: Mixed methods, user study methodology, quantitative methods, qualitative methods.

1 INTRODUCTION

Cross Reality (CR) deals with complex research questions, as it combines different stages of Milgram's Reality-Virtuality Continuum (RVC) [17]. This adds an additional layer of complexity as different virtual contexts need to be considered within one prototype. This means, that CR prototypes are not only technologically more challenging than individual Augmented Reality (AR) or Virtual Reality (VR) prototypes, but also often require different interaction and navigation metaphors from the individual domains. In collaborative scenarios, moving along the RVC also has major implications on the communication between participants. The additional layer of the RVC also means that it is harder to isolate effects towards a clear causal relationship.

There are multiple different approaches and open research areas with technology driven research, evaluation of perceptive concepts and application based research all being equally valid and relevant. To evaluate these complex research questions, it is useful to collect evidence from different perspectives and multiple theoretical approaches. In this and related communities, there have been discussions around how user studies are and should be conducted for several years [15, 14, 8, 7, 16, 10, 25]. While some emphasise the lack of qualitative approaches [14, 10], others focus on improving the methodology and reporting of quantitative studies to avoid a replication crisis [25]. We believe that there is benefit in going beyond these two separate methodologies. Mixed methods could be a useful approach to formalise this research process, as it allows to synthesise qualitative and quantitative data to gain comprehensive and valid insights.

To demonstrate the relevance of mixed methods research, we first discuss the methodological background of the individual methodologies to outline the underlying assumptions of these approaches.

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We then analyse how the individual methodologies have been applied in selected published user studies in cross reality and discuss their benefits and drawbacks. Finally, we summarise deliberations that should be taken into account when applying mixed methods methodology in user studies.

2 BACKGROUND OF RESEARCH METHODOLOGIES

Both qualitative and quantitative methods used for user evaluation were adapted from methods used in social science [4]. However, qualitative and quantitative methodology are based on different epistemological assumptions, i.e. different philosophical theories of how knowledge is generated as opposed to opinions.

Quantitative methodology results from positivism or postpositivism [4, 3]. This methodological approach is based on the assumption that there is an objective truth. To get to this truth, quantitative methodology seeks to avoid all subjectivity in the knowledge seeking process. It follows a deductive approach where concrete, testable hypotheses are formed before the data is collected. The data is then used to specifically test these a priori hypotheses. In human-computer interaction the most common approach to do so is through controlled experiments. This allows researchers to minimise confounding variables to infer a causal relationship between dependant and independent variables in a statistical data analysis.

Qualitative methodology, on the other hand, is based on interpretivist or constructivist views [4, 3]. The base assumption here is, that there is no objective truth. Instead there are multiple perspectives and research that is conducted by and with humans can not be objective. In contrary to positivist approaches, subjectivity is seen as a tool to interpret data in its context. Qualitative Research is based on an inductive theory building approach, meaning that based on a research question data is collected and based on this data, theories are formed. In human-computer interaction, qualitative methodology is often used in user studies where the participants perform a specific task or explore a tool. The data collection methods that are then used are often a combination of observation and interviews.

The mixed methods methodology is based on pragmatism or realism [2]. Pragmatism is however the dominant approach that is based on the belief of using the methodology that works best, i.e. that fits the research question. Thus, mixed methods approach draws on both qualitative and quantitative data collection and analysis method to gain knowledge. This allows for a combination of the inductive, qualitative theory building approach and the deductive theory-testing approach of the quantitative methodology.

There are different research designs for mixed methods research. Qualitative and quantitative data can either be collected within the same study or by conducting a quantitative and a qualitative study [6]. This depends on the research questions and the remaining study parameters. It is also necessary to consider the different requirements of qualitative and quantitative methodologies. When conducting two separate studies it can be classified into an explorative and an explanatory approach, according to the sequence of the studies. For the explorative approach the qualitative study is conducted first to form theories and the quantitative study is then used to test these theories to enable generalisation. In the explanatory approach, the quantitative study is conducted first to test whether an a priori hypothesis is true. The qualitative study is then added to explain the background of why this theory is true or is not true.

3 APPLICATIONS IN CR RESEARCH

After discussing the background of the research methodologies, we now look at how they have been applied in user studies in CR. Therefore, we discuss published work that includes user studies in CR and describe how the study methodologies have been applied. We also discuss limitations and advantages of the methodologies, based on how they are applied. The selection of publications is not a complete representation of user studies in cross-reality, but rather provides examples for the methodologies and their application in real CR research.

3.1 Quantitative

Pazhayedath et al. [18] conducted two within-subjects user studies on pinpointing techniques for CR collaboration. These techniques are used for communication between one user immersed in VR and one non-immersed user who wants to draw the attention of their collaborator towards a specific object in the virtual environment. In the first study, three different techniques, one of which posing as a baseline condition, are compared using an objective measurements of completion time and subjective measures of standardised and custom questionnaires. While these questionnaires are referred to in the publication as “qualitative” measures, they are in fact subjective quantitative measures as the questionnaires use Likert scales instead of open-ended questions. The results are then analysed using null-hypothesis significance testing. In the second study, the two main conditions were further developed to enable bi-directional communication between the participants. This was again evaluated through standardised and custom questionnaires and some statements by participants are mentioned, without indication whether they were collected during or after the study. These study designs are typical for quantitative studies where hypotheses are tested for significance by manipulating an independent variable, in this case pinpointing techniques and measuring the effect of this change on the dependent variables of completion time and questionnaire responses. The results here can tell us whether a one condition outperformed the other condition, but not why this is the case. Additionally, design decisions of how exactly the pinpointing techniques were implemented influence the results and therefore pose a limitation to the study. Since every study has limitations, the key point is to not overestimate the results of a single quantitative study. Instead, multiple studies using different scenarios might be necessary to understand how pinpointing techniques for CR collaboration should be applied.

While these two studies also include subjective questionnaire data, Schwajda et al.[20] focus solely on objective data when reporting on three quantitative studies on transforming graph data from 2D to 3D in AR. They use measurements of time and error to investigate different interaction techniques, data groupings and visual links in the transformation of a node-link graph from a large 2D screen to a 3D representation in AR. For more reliable mean based statistical data analysis, each participant completed four trials per condition. The first of these trials was a demo trial that was not included in the data analysis. Therefore, for example, in the first study with three conditions and 19 participants a total of 171 trials were collected for the data analysis. In contrast, in the first study of Pazhayedath et al. [18] with eight participants and three conditions only 24 data points were analysed. Therefore, the statistical power of the data analysis is too small for generalisable conclusions. But not only the amount of participants but also the sampling strategy impacts the generalisability of results, as the target population needs to be accurately represented

Two further studies on CR collaboration use a quantitative within subjects approach. One investigates the level of involvement of a non-HMD user on their user experience when in visiting a virtual museum together with an HMD user [23]. User experience is measured using a questionnaire. It is however, not specified if this was

a custom questionnaire or a standardised one. The second study in this area by Xia et al. [24] focuses on evaluating a system for collaborative CR. The system was developed for PC and HMD and the evaluation collects data on the user experience of this system in three different contexts. For the data collection, two standardised questionnaires are used that also provide a benchmark dataset. While the study uses a quantitative within subjects design, there is no comparative data analysis. Instead, the scores for the questionnaires are calculated and then compared to the benchmark dataset.

Overall, quantitative studies are useful for testing preexisting hypotheses. They do, however, not provide information on the background of these results. Additionally, design decisions in the implementation and task design have a great influence on the results. Ideally, quantitative studies allow researchers to draw generalisable conclusions. Therefore, it is necessary to apply appropriate sampling strategies and to achieve sufficient statistical power by using a large enough sample.

3.2 Qualitative

In the context of CR, qualitative methodology is often used to gather feedback and insights from experts.

Hubenschmid et al. [13] developed a study analysis tool for mixed reality user studies that is in itself a CR application. It allows users to analyse and watch the study data both in situ and ex situ. Therefore, users can switch between a desktop view for both modes and an immersive view for the in situ analysis. Since this tool specifically focuses on researchers in the field and not intended for use in the general population, the user study is only useful when conducted with users from this domain. The qualitative expert study conducted by Hubenschmid et al. [13] allows for a holistic perspective of these domain experts and systematic feedback integration. In the study, participants were first required to complete specific analysis tasks based on a real study analysis process in a guided phase. This phase familiarised the participants with the analysis tool and its features. This was later followed by a free exploration phase of a different dataset. For the data analysis Hubenschmid et al. [13] employed a thematic analysis approach [5]. This is an inductive process where the qualitative artifacts such as transcripts and videos are coded to summarise their content. The codes are iteratively refined clustered to find emerging themes in the data. In this case, the coding was performed by one researcher and the codes were checked and validated by two further researchers. This qualitative analysis delivers deep insights into what experts need from a data analysis tool for mixed reality user studies. It allows to draw conclusions on which aspects of the concept worked and which didn't as well as directions for future research and implementation. While experts are able to imagine how to use this tool for their own data, the results are not generalisable to all data and every use case. For qualitative expert studies, it is especially relevant to provide details on the background of the experts to accurately represent who was included in the study. In this case, for example, it could be a limitation, that the experts were all computer scientists working in similar fields at the same university. Therefore, their approaches to studies and data analysis might be at least partially similar. However, the reporting of allows users to accurately estimate the influence of this factor.

The qualitative expert evaluation was also used for another tool targeted at researchers. However, instead of the data analysis phase, the VRception toolkit focuses on rapid prototyping of CR systems [11]. The idea here is to simulate all stages of the RVC [17] in virtual reality. For the expert study, the researchers used their prototyping toolkit VRception to create prototypes of published work and present them to the original authors of the study. The authors were presented with their own and other recreations of published prototypes and were introduced to the functionality of VRception, before being interviewed. Then, an open coding approach was per-

formed the codes were further clustered into categories using an affinity diagram [12]. While it is not specifically called a thematic coding process, it certainly reads similar to the process applied by Hubenschmid et al. [13]. This emphasises that there is currently no unified way of reporting qualitative coding. After reporting on the expert study, Gruenefeld et al. [11] also report a remote interview study, where four pairs of two collaboratively created rapid cross-reality prototypes using the VRception toolkit. While this study includes some quantitative metrics, such as task completion time and responses to standardised questionnaires, this data was only used in a descriptive manner with the focus of the study lying on the qualitative interview data, using the same analysis process as for the expert evaluation.

The approach of a presenting a prototype to domain experts, followed by a semi-structured interview was also used in different domains such as surgery planning. Aigner et al. [1] presented four cardiologists with a cross-reality prototype that allowed them to look at the volumetric representation of a heart and its inner structures. The use case for this scenario is surgery planning. After a guided tour of the prototype and a free exploration phase of the model, the semi-structured interview was conducted. The analysis also used an open coding approach, but described in less detail as the focus of the publication lies on the introduction of the application. The qualitative expert study is here used as a way to get early feedback and understand the usefulness of such a prototype for surgery planning. In such early pilot studies, a small scale qualitative study is often a good fit for understanding the users' way of working and the suitability of the proposed tool.

In summary, qualitative methodologies are useful to gain an extensive understanding of what experts need and how they use a tool, as well as to get early feedback. Since qualitative results are inherently subjective, it is even more important to report the results in a way that conveys their relevance in the context of use. It is also indispensable to clearly describe the analysis process to enhance the transparency of how the results were formed. A common procedure in the context of CR is to provide a demonstration and/or free exploration of a prototype to the domain experts, followed by a semi-structured interview. The first part of this procedure allows researchers to present their ideas to the experts and demonstrate the possibilities of a tool. Data is mainly collected through interview data and observation, and the analysis is typically performed using inductive open coding approaches.

3.3 Mixed Methods

Friedl-Knirsch et al. [9] use a mixed methods approach to analyse the influence of the different types of AR devices in a collaborative data analysis process. Each of the three users in a group therefore uses a different AR device as well as a laptop during the task. They pose three research questions which are answered by collecting quantitative and qualitative data for each of them to cross validate and support the findings from different methodological perspectives. For the quantitative aspects, speech times, interaction log data, and several standardised and custom questionnaires are used. For the qualitative aspects, observation and interview data are collected. A within-subjects design was applied where each of the participants worked with each of the device types. In the end, a semi-structured group interview was conducted. A limitation of this study was the selection of measures to characterise the collaboration, which relied mainly on verbal communication on the quantitative side. While collaboration was also part of the observation and the group interview, there are also more quantitative measures to characterise collaboration.

Also in a collaborative scenario, but with a focus on analysing collaboration where users could transition between different stages on the RVC, Schröder et al. conducted a study using a spatial optimisation task. For the quantitative part of the study, the users'

position in the virtual environment, their stage on the RVC and interactions with the prototype were logged. Additionally, multiple standardised and custom questionnaires were applied. For the qualitative data collection, the sessions and interviews were recorded and a handwritten log was kept to note observations that were later discussed in the interviews. In the data analysis, the qualitative data was analysed first to identify commonalities and differences in the collaboration, mainly through affinity diagrams. Then the quantitative data was analysed in the process of deriving the analytical lenses for the collaboration. While the result is a synthesis of qualitative and quantitative data, the analysis process deviates from traditional quantitative data analysis, as the hypotheses were formed after the data collection.

Seraji et al. [21] used a between-subjects mixed methods design to investigate user behaviour patterns in the context of CR immersive analytics, comparing visual data analysis on a desktop to their CR system HybridAxes. In terms of qualitative data, they collected notes during the experiment, recorded the sessions and captured the screen of the devices. On the quantitative side, each action and the status of the system, as well as head hand and gaze movement were logged. In the analysis procedure an open coding approach was applied to the qualitative data, which was analysed first. Like in the study by Schröder et al. [19], the quantitative data was then used afterwards to quantitatively characterise the usage patterns from the qualitative findings.

A less common approach to mixed methods research is provided by Wang et al. [22]. In this study, the qualitative elicitation study method is applied to gather their preferred input methods for transitions of 3D objects in CR. The data is collected by asking participants about their preferred interaction methods for 20 different scenarios. While the collected data is qualitative, the data analysis is focused on quantifying participant agreement on the different input methods. Therefore, this provides a quantitative perspective on qualitative data. Nevertheless, this focus on the quantification also leads to a lack in qualitative explanation of the participant's reasoning for their proposed input methods.

Overall, mixed methods enables the combination of different methodological viewpoints to derive valid and comprehensive conclusions for complex research questions. This combination of different methodological perspectives, however, also comes at a price. While cross validation is a good way of forming reliable results, it is not always possible to find quantitative evidence for qualitative reasoning, especially in studies that collect quantitative and qualitative data at the same time. By mixing qualitative and quantitative methods in an individual research design, it is difficult to follow all the procedures and requirements for each methodological approach. For example, when trying to cross validate findings from qualitative data analysis with quantitative data [21, 19], it is not possible to form hypotheses ahead of the data collection, since they are inductively generated during the qualitative data analysis.

4 CONSIDERATIONS WHEN USING MIXED METHODS RESEARCH

In this section, we discuss considerations for using mixed methods study designs in CR.

Data synthesis is key One key aspect of the mixed methods approach is to synthesise the data in the findings. This means that collecting some qualitative and some quantitative data in a study is not per se a mixed methods approach. Instead both data collections should serve a coherent goal. This can for example be cross validating findings with quantitative and qualitative data [19, 21]. This entails collecting data on the same phenomenon from both perspectives. Another approach would be to look at different aspects of the same research question using different methods [9].

Different methodological requirements Each methodological approach has different requirements and assumptions for a user study. Especially in an approach that collects both types of data in one user study, these requirements can be difficult to combine. This is for example the case regarding the inherent difference of the inductive theory building approach of qualitative methodology and the deductive theory testing approach of quantitative methodology means that. There is a risk to violate either the requirement of quantitative research to form the hypotheses before data collection, or the assumption of theories being built inductively from the data.

There is no perfect research design Research designs need to fit their purpose. Depending on the domain, the available resources, the researchers involved and other environmental factors, a different research design may be the most suitable. While the study design needs to fit the research question, the research question itself depends on the framing and interpretation of the researchers. In the process of designing a user study, it is also necessary to make decisions on what and how to measure. Each decision has consequences with their benefits and drawbacks. This means that every user study has limitations.

Clear presentation is key With mixing different methodologies there is increased potential for confusion. Combining qualitative and quantitative methodologies and approaches, adds complexity to the publication as there are even more possibilities for research designs, than with purely qualitative or quantitative research. For readers to correctly interpret the study and its results, it is therefore indispensable to aim for perfectly clear presentation in the publication. Readers must be aware which part is quantitative and which is qualitative. This includes using the correct wording, explicitly stating the research question and its operationalisation and actively pointing towards the limitations of the study.

Purely quantitative or qualitative research is still valid While combining qualitative and quantitative methodologies to form a broad basis for the results of the study might seem like a solution for almost any situation (and a way to comply with all reviewer requirements) it is not suitable for all research questions. For example, when the only goal of the research is to draw generalisable conclusions, a quantitative approach is the most suitable. Moreover, studies should not be rejected for not including both types of data, even if both data types would be applicable. Mixed methods approaches can also be split across multiple studies and publications in order to provide methodologically clear and precise quantitative or qualitative studies.

Required resources Combining both quantitative and qualitative methodologies drastically increases the resources necessary for a user study. Qualitative data analysis is a time consuming endeavour, with large amounts of unstructured qualitative data that need to be revisited. Additionally, it requires more than one researcher to at least check and validate the results in the data as subjectivity is inherent for the method. Additionally, researchers need to be experienced in both types of data collection and analysis. However, there is also the issue of enrolling participants for the study. Complex study designs often require more time per session making it harder to find enough participants for the study.

5 CONCLUSION

In this position paper, we emphasise the relevance of mixed methods study designs for cross reality research. After discussing

the background of qualitative, quantitative and mixed methods research, we analyse selected examples from published user studies in cross reality and discuss how the methodological approaches are applied. Furthermore, we elaborate on the benefits and drawbacks of the methodologies and discuss considerations for the practical application of mixed methods methodology.

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