# Comparing Synchronous and Asynchronous Task Delivery in Mixed Reality Environments

Lara Sofie Lenz, Andreas Rene Fender, Julia Chatain, Christian Holz

**Abstract**—Asynchronous digital communication is a widely applied and well-known form of information exchange. Most pieces of technology make use of some variation of asynchronous communication systems, be it messaging or email applications. This allows recipients to process digital messages immediately (synchronous) or whenever they have time (asynchronous), meaning that purely digital interruptions can be mitigated easily. Mixed Reality systems have the potential to not only handle digital interruptions but also interruptions in physical space, e.g., caused by co-workers in workspaces or learning environments. However, the benefits of such systems previously remained untested in the context of Mixed Reality. We conducted a user study (N=26) to investigate the impact that the timing of task delivery has on the participants' performance, workflow, and emotional state. Participants had to perform several cognitively demanding tasks in a Mixed Reality workspace. Inside the virtual workspace, we simulated in-person task delivery either during tasks (i.e., interrupting the participant) or between tasks (i.e., delaying the interruption). Our results show that delaying interruptions has a significant impact on subjective metrics like the perceived performance and workload.

**Index Terms**—Mixed Reality, Workspaces, Interruptions, Evaluation, Task focus

## 1 Introduction

Office environments require employees to stay concentrated while also being generally available to interact and communicate with. However, several studies suggest that interruptions have a disruptive and negative impact on performance and should therefore be avoided [27, 43, 52]. Van Solingen et al. [65] found out that subjects spent 1-1.5 hours per day on interruptions which is equivalent to ~20% of the work time. Purely *digital* communication has the advantage of conveying information while allowing the recipient to delay the reception (e.g., muting instant messaging devices), but this is not trivial for *physical* (or face-to-face) communication, in which interruption cannot be mitigated efficiently. Simply making a person unavailable for a time (e.g., by leaving a note at their office door) does not suffice [6, 15], and the responsibility for avoiding physical interruption resides at the initiator of the communication (e.g., entering a colleague's office).

In the last few decades, Mixed Reality (**MR**) applications have been experiencing a significant rise in popularity. Virtual Reality (**VR**) is already successful in the gaming market and an increasing number of researchers, practitioners, and consumers see potential for VR/MR in future office spaces. Immersion, seamless remote collaboration and practically infinite space for virtual 2D and 3D contents are advantages over desktop environments, which will likely lead to MR devices slowly becoming commonplace in offices–once technology and ergonomics are mature enough. Often overlooked aspects of MR workplaces are the challenges and opportunities with regards to spontaneous co-located interactions. More concretely, how we communicate in office spaces and deal with *interruptions*, can be fundamentally different compared to today and immersive technology has the potential to not only mitigate digital interruptions but also *physical* interruptions. This is because of the unique capability of MR technology to not only integrate but also alter our perception of the physical space. This can be achieved either through external depth cameras [22, 40] or with fully self-contained headsets that can seamlessly switch between full immersion and passthrough (e.g., `Apple Vision Pro` [3] or the `Meta Quest` series [46]). Not only does it enable deferring interruptions (e.g., caused by delivering new tasks) but also physical objects can

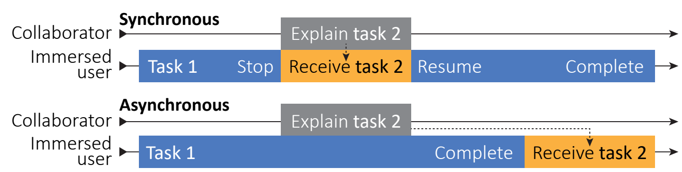


Fig. 1: By selectively blocking, recording and playing back physical events, MR technologies can defer interruptions in physical space.

be visually concealed, until they become relevant for the task. This way of handling physical interruptions can be seen as an instance of an *Asynchronous Reality*. Fender and Holz [22] conceptualized and prototyped such an Asynchronous Reality system, whereas interruption handling was their primary use case. However, the feasibility of those new types of systems from a usability and perception perspective was previously untested, in particular for various specific situations and use cases of communication. Therefore, the research question arises: How would an asynchronous MR system be perceived by users when working on specific tasks? More concretely, while technology that makes MR offices feasible is still evolving, we already need to understand, how MR based interruption handling in physical space performs from a human-factors perspective.

To contribute to this research trajectory, we evaluated specific aspects of communication in such an environment. Concretely, we conducted a study that simulates *in-person task delivery* in a hypothetical future MR office environment. In the study, tasks are either delivered **synchronously** (interrupting an ongoing task) or **asynchronously** (delivered after the current task finishes). We found that while objective performance improvements are only marginal in many cases, the subjective perception of the participants' performance was significantly higher with the asynchronous system. Participants felt less frustrated and stressed when receiving tasks asynchronously and they generally preferred the asynchronous system over the synchronous one. Our results imply that asynchronous MR communication systems are comparable in performance to currently-applied *purely digital* communication systems and might even provide some aid regarding one's ability to concentrate and minimize task switch overhead.

Taken together, our main contribution is an MR study in which we investigate the effects of asynchronous communication on both the workflow and the performance of participants when compared to synchronous communication. Our setup simulates a future context-aware office environment in which the participant works on a sequence of tasks while a collaborator gives verbalized task instructions and pro-

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vides task-related physical objects. Depending on the condition, the participant is either interrupted with a task or those interruptions are deferred to the moments between tasks (*synchronous* and *asynchronous*, respectively, in Figure 1). Such an idealized system allows us to investigate MR interruption handling from a human factors perspective and helps inform the design of collaborative future MR office spaces.

## 2 Related Work

We aim to leverage the insights from two main bodies of research: *effects of interruption* and *communication in MR*. Therefore, in this section, we first seek to understand the general effects of interruption and mitigation techniques. Then, we describe how previous systems facilitated synchronous and asynchronous communication in MR.

### 2.1 Interruptions

Interruptions have an impact on our everyday lives, but some interruptions are more disruptive and disturbing than others. Much previous research investigated the effects of digital or physical interruptions, what aspects might be affecting the perception of interruptions, and how to mitigate them effectively. Interrupting tasks that have a similar nature to the interrupted task are more disruptive than dissimilar ones [12]. Moreover, the length of the interruptions and the mental workload can have an impact on the 'disruptiveness' of a task. More concretely, longer interruptions increase the rate of sequence errors [2], and the timing of an interruption has a significant effect on resumption time [50]. Whenever users have the chance to defer interruptions, they have the tendency to finish tasks in sequence until the workload decreases [60]. Multitasking might also indicate negative feelings regarding the task progress and prospects of goal achievement, which in the end lead to self-interruptions [1]. Users with negative feelings like frustration, obstruction, or exhaustion choose to stop their work more often to regain energy, or in hopes of improved task accomplishment [1, 60]. Interruptions become especially disruptive whenever the interrupting tasks start to get nested [61] or the person handling them fails to manage their cognitive resources [19]. Mental resource handling is the biggest issue when facing interruptions, as the person getting interrupted should neither abandon the current task, nor forget about the new one leading to a dilemma in the order of processing. Functionalities for reminding the person can help manage suspended tasks, but create the risk of additional interruptions [49].

The consequences of interruptions are manifold: Mark et al. suggest that people compensate for interruptions by working faster and thereby putting up with stress, higher frustration, time pressure, and effort [44]. Interruptions can even have a disruptive effect on a person's emotional state. Lacking control over potentially stressful stimuli increases anxiety and the unavailability of alternatives can lead to a feeling of helplessness [4, 42]. The disruptive effect of interruptions is most noticeable in and around workplaces [39] and learning environments [20]. Whenever work-related interruptions occur, they affect one's personal life to a greater extent than interruptions from one's personal life affect one's work [9].

#### 2.1.1 Problems and benefits of interruptions

In spite of all the negative effects, interruptions do not always have to be harmful. They can also have a stimulating, exciting effect or could be used to reorganise one's priorities [1], and they could even lead to faster perceptual processing [58]. 64% of the time, recipients gain a benefit from being interrupted. The problematic aspect is that over 40% do not resume their prior work which leads to abandoned tasks if no reminding functionality exists [52, 62]. Minassian et al. [48] found that office workers in large software companies advertise their availability to their co-workers to defer interruptions and put reminders for handling interrupting tasks later on. Furthermore, they found out that interruptions can also be intentionally self-inflicted to socialise, improve, or complete an actively worked-on task.

#### 2.1.2 Techniques for handling interruptions

The negative effects of interruptions can be reduced either through training or in combination with technology. Excessive training under interruptions [32], brain stimulation [8], or controlling the timing of the interruption [25] are only a few techniques that can diminish disruption and improve performance. A large portion of today's work-related interruptions are technology-mediated. Here, the effect highly depends on the medium through which the interruption was received. Phone and messaging interruptions have a generally negative connotation [13, 19], whereas emails allow for task closure which can lead to the positive feeling of completion. Nonetheless, using such devices has an impact on face-to-face interactions. The amount of time spent actively paying attention to the speaker is correlated with the perception of the content being more interesting [10, 41].

Especially for technology-mediated interruptions it is of essence to know how disruptive an interruption can be. To evaluate this, interruption cost models are frequently used [33–35]. Interruptions are always to some extent disruptive, that is why, if an interruption cannot be avoided, it should be made possible to delay the interruption until an opportune moment arises [5]. Especially instant messaging interruptions during fast, stimulus-driven search, list evaluation, or typing tasks are harmful to the performance of the user. That is why users have a tendency to divide tasks into logical blocks of completion to minimise overhead when switching to a different task [11, 13]. The disruptiveness of an interruption is reduced when either the incoming message is highly relevant to the current task or when it is interesting to the recipient [14, 23, 28]. Nonetheless, Kushlev et al. [37] discovered that participants are more inattentive and hyperactive when their phone interruptions are active, leading to lower productivity and well-being. Decreasing the alerts does not necessarily bring an advantage either since fewer phone interruptions can lead to anxiety and the perception of missing information. Batching notifications instead has been shown to bring more benefits [24].

### 2.2 Communication in MR

While the previously discussed general aspects of interruptions in workspaces have been researched for a long time, the emergence of immersive technology creates new challenges and opportunities. Face-to-face communication is an intricate and complex process. While verbal cues deliver merely what was said, non-verbal cues help to put the information into context. This does not only play a major factor for in-person interactions, but also for communication in VR which can be just as high-fidelity as face-to-face communication [17]. Knowing that VR-mediated interactions can be as valuable as in-person exchanges leads to new ways of communication without sacrificing the quality of the discourse or implicit cues. To provide a foundation for collaboration, good communication is of essence, but to provide adequate channels of communication, we must take the different spatial and temporal situations into consideration under which these interactions may take place [18, 56].

#### 2.2.1 Synchronous communication in MR

*Synchronous* communication refers to interactions, in which all communicating participants receive the information at around the same time at which it was conveyed and respond immediately. Synchronous MR communication is not limited to the instantaneous transmission of verbal cues and body language but may also involve shared interactions with objects and environments, even if the participants are not in the same space (i.e., remote synchronous interaction).

Several synchronous MR systems exist that aimed to exploit the interactability of users in different spaces [29, 55, 57]. It was found that seeing other users and part of the physical environment can improve awareness and performance, since users can freely interact with people and objects from the real world without having to break immersion [7, 31, 45, 54]. Since getting used to this mix of environments can be difficult, Roo et al. [59] introduced a system to seamlessly switch between physical and virtual interactions in a collaborative setting. Such mix of realities is not limited to visuals. For instance, O'Hagan et al. [53] explored the role of audio in the communication between MR users and bystanders.

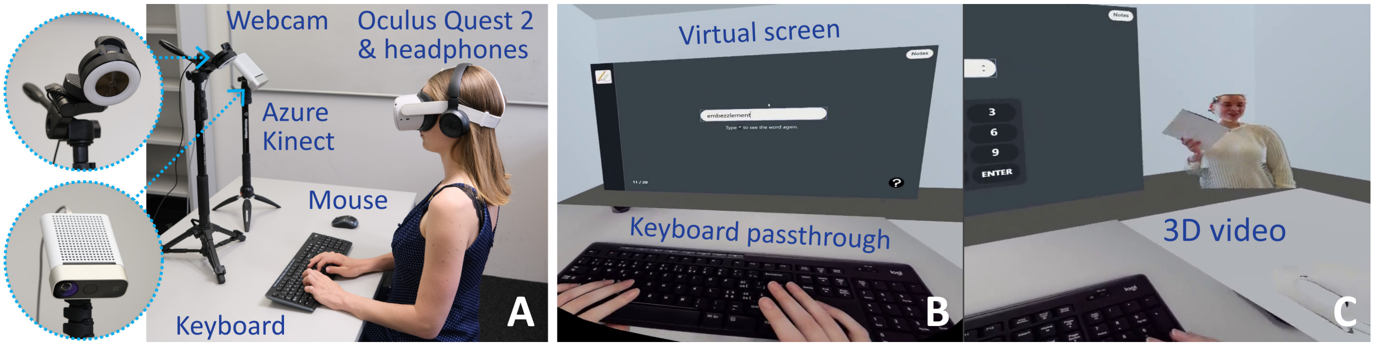



Fig. 2: Overview of the hardware and virtual environment of our study apparatus. A) We use an Oculus Quest 2 headset, a webcam on a tripod pointing at the keyboard as well as an Azure Kinect pointing at the mouse (or other objects depending on the task). B) Participants see a virtual floating screen running the task interfaces as well as the passthrough of the keyboard region. C) The pre-recorded instructor provides information and objects. Here, a physical piece of paper with key information about a task is given to the immersed participant.

#### 2.2.2 Asynchronous communication in MR

In contrast to synchronous communication, asynchronous interaction systems are flexible in time meaning that information can be repeated or delayed for an arbitrary amount of time. Some of the interruption handling techniques make use of fully-immersive set-ups to control the environment. However, people working in such set-ups fear disengagement from reality, e.g., due to fear of missing out or because of security risks [25, 26]. Asynchronous MR communication systems can be practical in various situations. One can change the speed at which information are presented or one can let the user navigate through time via object-based tracking [36, 38] while preserving the context of the information. Fender and Holz propose an *Asynchronous Reality* [22] as a means to delay the perception of physical events for various use cases. However, while they suggest interruption handling during focused work as one of the use cases, their and related approaches that utilize immersive asynchronous communication still remain to be investigated from a human factors perspective.

## 3 MR FOR INTERRUPTION HANDLING

As discussed above, the general negative and positive effects of interruptions have been researched extensively, e.g., in workplaces. Asynchronous digital communication systems can defer certain types of interruptions (task instructions, deliveries etc.) to suitable moments in time. In particular, with the increased interest of using MR in workplaces and new ways of intertwining physical and digital spaces, researchers started looking into the implications and opportunities of such technologies for interruption as MR interfaces can not only handle digital interruptions but potentially co-located physical interruptions as well. However, those opportunities have not been tested before.

Our hypotheses are inspired by previous work on interruption and re-contextualized for MR systems, i.e., in this work we want to test whether the following hypotheses hold true when comparing synchronous and asynchronous co-located MR communication.

- **H1**: *It is easier and faster to complete tasks when the interruption happens after the task is finished.*
- **H2**: *Users have a higher degree of accomplishment when they can complete tasks without interruptions.* The system allows for the tasks to be completed one after the other. This would lead to the participants never having to fear forgetting about another task.
- **H3**: *It is easier to resume and keep track of all tasks when the interruptions happen asynchronously.* This is due to the fact that the interruptions occur at phases of logical transitions.
- **H4**: *Users perceive a higher degree of control when interruptions are delayed.* An ideal system allows participants to process the interruptions at times of lower workload.
- **H5**: *Participants would prefer to use asynchronous over synchronous communication systems in terms of perceived workload.*

## 4 STUDY: DESIGN AND SETUP

The purpose of our study is to investigate the usability and practicality of asynchronous MR systems, what effects such systems would have on the participant's objective performance as well as on their individual perception of their performance. We test the benefits and trade-offs between synchronous and asynchronous co-located communication in MR under ideal conditions, i.e., with simulated fully functional synchronous or asynchronous communication modes, respectively. Our tasks are simplified versions of knowledge work tasks and learning exercises. The study was approved by the local ethics committee of our institution. The supplemental materials of this paper contain an appendix with additional details as well as a video figure, which shows the apparatus, virtual environment, tasks, and conditions in motion.

### 4.1 Study design

We followed a within-subject design, so as to not only gather quantitative feedback, but also qualitative feedback that lets participants directly compare the two modes at the end. Throughout the study, participants filled out several questionnaires (the full questionnaires are listed in Appendix A). For each questionnaire item, if not stated otherwise, participants respond on a 7-point Likert scale from 1 (strongly disagree/very difficult) to 7 (strongly agree/very simple).

### 4.2 Apparatus

#### 4.2.1 Hardware

Figure 2 A shows an overview of the hardware setup. Throughout the whole study, participants were seated at a table. During a task, participants were wearing a `Meta Quest 2` headset [46] as well as headphones. Participants used a wireless mouse and keyboard placed on the desk to control and navigate the task interface in MR. The input devices were connected to a second laptop hosting the local server. This laptop was also running our custom input application and thus forwarded the input events of the mouse and keyboard to the main laptop which controlled the MR aspects of the study. A `Razer Kiyo` webcam with a resolution of $1920 \times 1080$ pixels at 30 Hz pointed towards the keyboard. We rendered the cropped camera stream on a virtual horizontal rectangle co-located with the real keyboard such that the participants could see their own hands (Figure 2 B). In addition, a `Microsoft Azure Kinect` [47] on the right-hand side enabled live reconstructing parts of the desk, so that the participant could interact with task-related physical objects including the mouse.

#### 4.2.2 Software

As mentioned before, our aim is to explore synchronous versus asynchronous in-person task delivery under ideal conditions. Therefore, to reduce confounds and fluctuations in task completion time measurements, we pre-recorded 3D videos and used those to simulate interruptions instead of acting them out during the study. A transcript of the pre-recorded instructions and questions can be found in Appendix E.

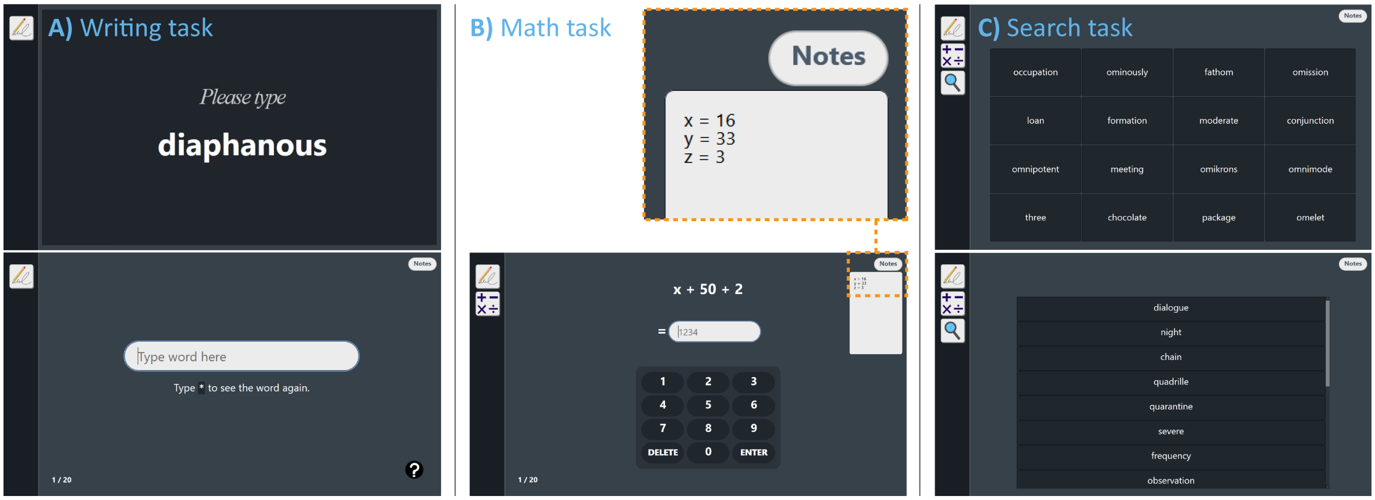



Fig. 3: Interfaces for the tasks of BLOCK 1. Throughout all tasks, participants can type information by using the 'Notes' field in the upper-right corner. (A) WRITING task. There is a text field in the middle of the window where the correct word has to be entered. To see the word again, participants can type the '*' symbol. (B) MATH task. Participants need to calculate and enter the result of a mathematical expression, some of which contain variables. The 'Notes' field is particularly relevant to note down values for variables. (C) SEARCH task. Participants have to click on words that were given on a physical piece of paper. The upper image shows the tile view, while the lower image shows the words arranged in a list.

The study ran inside the `Unity3D Engine 2020.3.14` [63]. We used the *Velt* framework [21] for handling camera streams (pre-recorded and live). We implemented the task interface (Figure 2 B) in HTML, CSS, and JavaScript and ran it as a local web server, which we rendered inside the MR environment using the `ZFBrowser` Unity plugin. Recording and playing back 3D videos (Figure 2 C) involved several libraries: We used *RVL* [66] for compressing the depth streams and `turbojpeg`[1] for compressing the RGB streams. We handled audio via `NAudio`[2].

### 4.3 Study tasks & procedure

The main part of the study consisted of two blocks. BLOCK 1 contained three sub-tasks (WRITING, MATH, SEARCH) that participants had to complete as quickly as possible and with as few errors as possible. BLOCK 2 consisted of a single open-ended task.

Figure 4 is an overview of our study procedure. The participant was greeted by the experimenter and filled out the consent form followed by the *Pre-questionnaire*. The *Pre-questionnaire* mostly contained questions about previous experiences with VR, their subjective ability to concentrate, and more. Notably, it contained one question about how the participant generally feels about interruptions as well as one question about how they typically handle interruptions. Both questions had categorical responses instead of Likert scales. All questions and possible responses can be found in Appendix A.1.

After filling out the *Pre-questionnaire*, the participant was introduced to the setup and then two or more minutes of TRAINING time were allocated for some warm-up tasks (simplified versions of the three sub-tasks of BLOCK 1) inside the virtual environment. After the TRAINING phase, the participant directly started with BLOCK 1.

#### 4.3.1 Block 1

The primary purpose of the first block was to collect quantitative subjective and objective data. We designed three tasks (started in fixed order) to be completed with two counterbalanced conditions: SYNCHRONOUS and ASYNCHRONOUS.

**WRITING** task (Figure 3 A). The system displayed a word for 1.5 seconds, which the participant had to memorize. The word then disappeared and the participant had to enter it into a text field. The participant had the option to see the word again, in case they could not remember it. By either entering the correct word or after three wrong

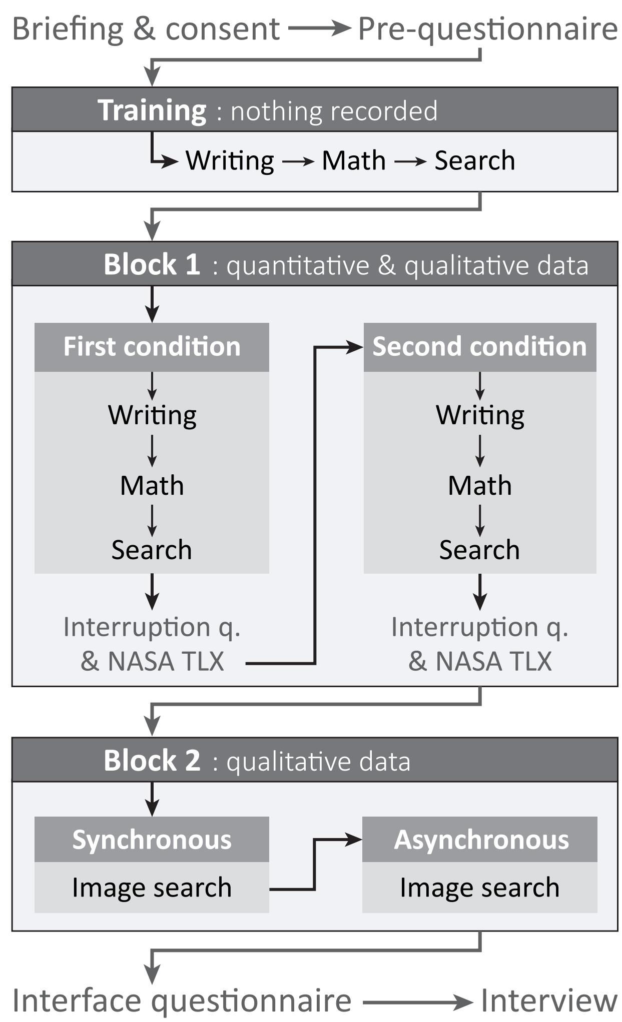
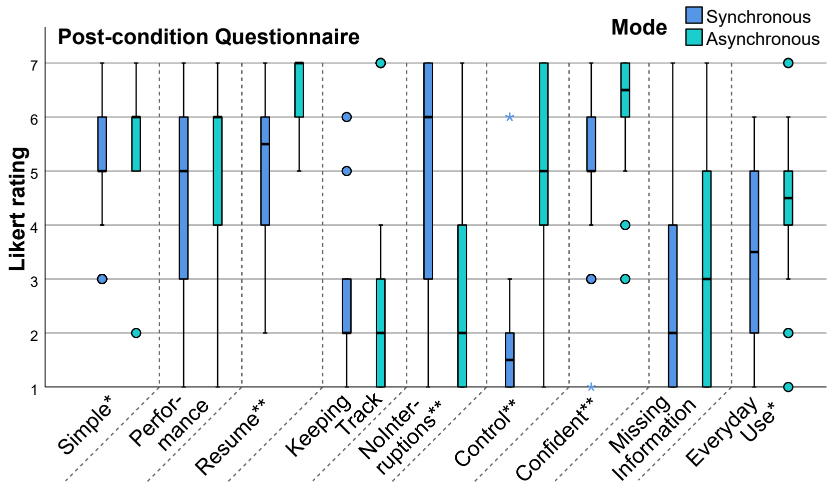



Fig. 4: Our study procedure including the sequence of tasks and questionnaires. The conditions within BLOCK 1 were counterbalanced (SYNCHRONOUS first and then ASYNCHRONOUS or vice versa).

[1]https://libjpeg-turbo.org/
[2]https://github.com/naudio/NAudio




| Question | $Z$ | $p$ |
|---|---|---|
| SIMPLE | 2.222 | **.026** |
| PERFORMANCE | 1.856 | .063 |
| RESUME | 3.509 | **< .001** |
| KEEPINGTRACK | -0.338 | .735 |
| NOINTERRUPTIONS | -4.124 | **< .001** |
| CONTROL | 3.908 | **< .001** |
| CONFIDENT | 3.462 | **.001** |
| MISSINGINFORMATION | 1.748 | .080 |
| EVERYDAYUSE | 2.696 | **.007** |

Fig. 5: Distribution of ratings in the *Interruption* post-questionnaire. * indicates ratings with $p < .05$, ** indicates ratings with $p < .001$. The table shows the *Standardized Test Statistic* $Z$ and the $p$ value of a Wilcoxon test comparing the two conditions for each item.

inputs, the system automatically proceeded with the next word. The participant needed to type 20 words in total.

**MATH** task (Figure 3 B). The participant had to calculate the value of 20 mathematical expressions of various difficulty levels. Some of these expressions contained variables, the values of which the pre-recorded instructor gave during or right after the previous task (SYNCHRONOUS or ASYNCHRONOUS, respectively). The participant could note down the values inside the interface (Figure 3 B Top).

**SEARCH** task (Figure 3 C). The participant had to search for a specific word (10 total) in a word cluster that was either formatted into a tile or list view. The words to search for were given on a physical piece of paper. If an incorrect word was selected the word disappeared and the participant had to continue searching.

As opposed to the two counterbalanced conditions, we do not compare tasks with each other. Therefore the task and instruction sequence is fixed. Depending on the condition, the participant was interrupted by a pre-recorded instructional 3D video either in the middle of the first and second task (SYNCHRONOUS condition) or at the end of each task (ASYNCHRONOUS condition) akin to Figure 1. More concretely, during the first interruption, a wireless mouse was given to the participant, along with instructions and an oral definition of the variables for the MATH task. The second interruption made a piece of paper available containing the words to be sought in the SEARCH task. The experimenter silently put the physical objects to interact with next to the participant at the appropriate moment during playback so that they could then physically interact with them afterwards (through the live reconstruction based on the `Azure Kinect`).

After each condition, the participant took off the headset and answered two post-questionnaires, namely the standard *NASA TLX* [30, 51] and a study-specific *Interruption* questionnaire. The latter contained questions on a 7-point Likert scale about specific aspects of the experience and subjective performance. Furthermore, it contained questions about how participants felt during interruptions and how they handled them (same as in the *Pre-questionnaire*). The full questionnaire can be found in Appendix A.2.

We measured the task completion times for each individual task and the whole block. Moreover, the experimenter observed how they handled interruptions, i.e., whether they switched between tasks.

#### 4.3.2 Block 2

The second block consisted of two image search tasks (using Google via the same virtual screen). The participant had to find a number of pictures on a specific topic. For that, they could take as much time as they needed. This block was solely used for qualitative feedback, so there was no strict definition of conditions. During the first topic (task: *search for four bears from four continents*), the participant was interrupted in the middle (synchronously). During the second topic (task: *search for animals with spikes*), the participant was interrupted at the end of the task (asynchronously). The interruptions were not essential for task completion but were rather used to have staged conversations with the participant to gain additional qualitative insights about such interactions.

#### 4.3.3 End of session

At the end of a session, the participant filled out an *Interface questionnaire* (see Appendix A.3), so that we could examine, to which extend the interface itself might have an effect on the answers regardless of the condition. In addition, we conducted a short semi-structured interview (based on a set of pre-determined questions listed in Appendix F) to collect some qualitative feedback from both blocks so that the participant could directly comment on asynchronous MR communication systems and how they compare to their synchronous counterparts. A session lasted about one hour on average. All participants were compensated with chocolate bars for their time.

### 4.4 Participants

We recruited a total of 26 participants (16 male, 10 female; aged 21-66 years, $M = 27.19$, $SD = 9.588$). Six participants stated that they never used VR devices before, eight have used them once or twice, four rarely, six occasionally and two use them regularly. The results of the *Pre-questionnaire* indicate that participants found it generally fairly easy to stay concentrated over short periods of time ($Q_{\text{PRE-CONCENTRATEDSHORT}}$, $Median = 6$), but slightly less over long periods ($Q_{\text{PRE-CONCENTRATEDLONG}}$, $Median = 5$) and that they would be interested in having a tool available that could help them stay concentrated ($Q_{\text{PRE-TOOL}}$, $Median = 6$).

## 5 STUDY: RESULTS

In the following, we report the quantitative and qualitative results obtained through the three questionnaires, various measurements of the task performance in BLOCK 1, experimenter observations, and interviews with the participants.

### 5.1 Quantitative Results

In this sub section, we visualize and report the analysis results of the subjective quantitative data (e.g., Likert ratings) as well as objective data (task completion times).

#### 5.1.1 Hypothesis testing

To test our hypotheses, we analyzed the *Interruption* post-questionnaire (Figure 5), the measurements of task completion times (Figure 6 Left), and the *NASA TLX* post-questionnaire results (Figure 6 Right). For each, we compared the Synchronous and Asynchronous conditions. We used Shapiro-Wilk to test for normal distribution of task completion times. All task completion times (total and per task) were normally distributed ($p < .05$), except for the Math task in the Synchronous condition ($p = .141$). We used a paired t-test for all normally distributed task completion times and a Wilcoxon test for all other measurements. We focus our attention on the most important results. A summary of the remaining results can be found in Appendix C and Appendix D.

- **H1**: *Partially shown*. While there was no significant improvement in overall task completion time, the task completion time was significantly shorter for the Writing task ($p < .001$, *Cohen's* $d = 0.81$, $t = 4.32$). That said, the time measurements for the three individual tasks are harder to interpret than the overall time due to the interruption playback during which participants could act in parallel. The *Total workload* (Figure 6 Right) of the raw *NASA TLX* was rated significantly higher in the Synchronous condition ($p = .009$). Furthermore, the sub scales *Performance*, *Effort*, and *Frustration* were rated significantly higher in the Synchronous condition (see Appendix D). The responses to $\text{Q}_{\text{Post-Simple}}$ (*"How simple was it to complete the tasks?"*) indicate that the completion of the tasks was significantly easier in the Asynchronous condition ($p = .026$).
- **H2**: *Partially shown*. $\text{Q}_{\text{Post-NoInterruptions}}$ (*"I think I could have performed better if there would have been no interruptions"*) was rated significantly higher in Synchronous ($p < .001$), and $\text{Q}_{\text{Post-Confident}}$ (*"I feel confident to have correctly completed the tasks despite the interruptions"*) was rated significantly higher in Asynchronous ($p < .001$). This hypothesis is only partially shown as other relevant questions were not significant. For instance, the *NASA TLX* sub scale *Performance* was significant ($p = .041$), but the *Interruption* post-questionnaire item $\text{Q}_{\text{Post-Performance}}$ (*"I was content with my performance during the study"*) was not.
- **H3**: *Partially shown*. $\text{Q}_{\text{Post-Resume}}$ (*"When I was interrupted, it was easy for me to resume the interrupted task afterwards"*) was rated significantly higher in Asynchronous ($p < .001$), while $\text{Q}_{\text{Post-KeepingTrack}}$ (*"It was difficult for me to keep track of what I had to do"*) was not significant ($p = .735$).
- **H4**: *Shown*. The question $\text{Q}_{\text{Post-Control}}$ (*"It felt like I had more control over the timing of the interruption"*) was rated significantly higher in Asynchronous ($p < .001$).
- **H5**: *Shown*. $\text{Q}_{\text{Post-EverydayUse}}$ (*"I could see myself using this in my everyday life"*) was rated significantly higher in Asynchronous ($p = .007$).

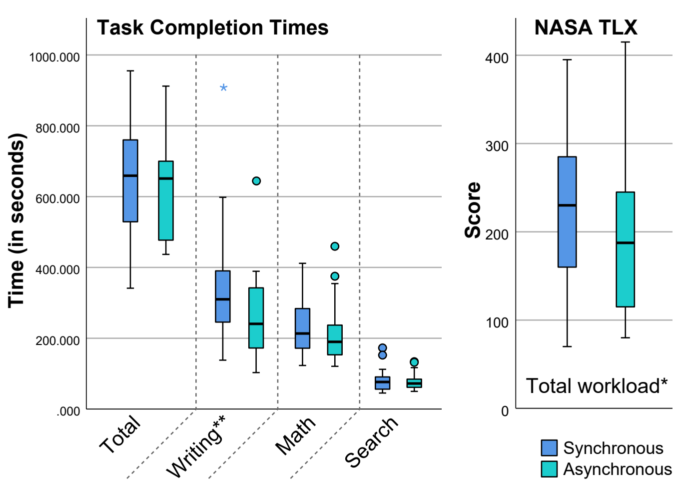



Fig. 6: Left: Completion times for the overall task block and the individual tasks. Right: Total workload measurements of the *NASA TLX* questionnaire. In both, * and ** indicate significance.

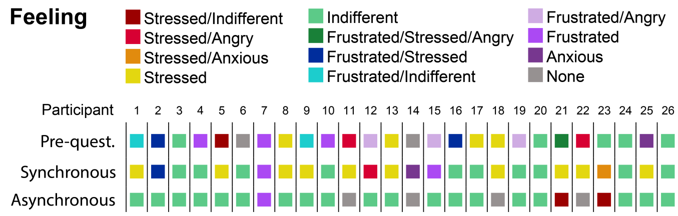



Fig. 7: Overview of each participant's feelings regarding interruptions in general (*Pre-questionnaire*), and after each condition, respectively.

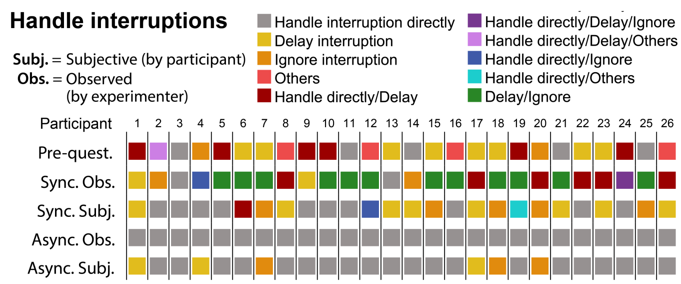



Fig. 8: Overview of each participant's interruption handling method in general (based on the *Pre-questionnaire*) as well as in the two study conditions. For each condition (denoted 'Sync' and 'Async'), we visualize what handling method the participant stated (denoted 'Subj') as well as what the experimenter observed (denoted 'Obs').

### 5.1.2 Feelings about interruption and interruption handling

In addition to the Likert-scale questions, participants had to indicate their feelings when getting interrupted and how they handled the interruption. Here, we describe our observations and findings with regards to the categorical data.

As shown in Figure 7, participants reported less negative feelings regarding interruptions when the interruption occurred at the end of a task (Asynchronous). Furthermore, the visualization indicates large subjective differences in terms of how participants feel about interruptions as well as discrepancies between the *Pre-questionnaire* answers and the answers in the conditions.

Figure 8 shows the different techniques applied to handle the interruptions. The visualization shows the *subjective* answers of the participants from the *Pre-questionnaire* as well as for the different conditions. In addition, the figure contains the *observations* made during the study by the experimenter (*Subj.* and *Obs.* in Figure 8). As presented in the visualization, there is a noticeable discrepancy when comparing the assessments of the user and experimenter. In particular, interruptions are always handled directly in the Asynchronous condition as per task design. Yet, some participants reported that they delayed or ignored the interruption.

### 5.1.3 Interface

To make sure the results are not skewed by the interface, we asked participants about the interface at the end of the study. All 7-point Likert scale responses of the *Interface questionnaire* are plotted in Appendix B. The interface in general was rated to be easy to understand and use ($\text{Q}_{\text{Interface-Simple}}$, *Median* $= 7$). Furthermore, we wanted to find out whether our system setup choices were inhibiting performance. Concretely, we initially experimented with live 3D reconstructing the keyboard as well. However, we realized during development before the main study that using a simple RGB stream without relying on specialized sensing or tracking turned out to be more robust and easier to work with. Therefore, we use different types of cameras for the keyboard versus the mouse or other objects. The *Interface questionnaire* confirmed that participants did not find it difficult to interact with objects ($\text{Q}_{\text{Interface-FindObjects}}$: *Median* $= 2$; $\text{Q}_{\text{Interface-MouseKeyboard}}$: *Median* $= 5$), and that not too much disturbance is introduced when seeing one's own hands ($\text{Q}_{\text{Interface-DisturbedByHands}}$: *Median* $= 1.5$).

## 5.2 Qualitative Results

During the semi-structured interviews in which the experimenter asked participants about their experience in both blocks, almost all participants stated that they preferred using the asynchronous communication system over the synchronous one and agreed that they felt more productive and faster during the asynchronous mode. "*I just noticed that interruptions, if you don't essentially bundle them, then they really interrupt your workflow more intensely*" (P16). "*I think it could be really useful for longer tasks. [...] Especially for receiving task instructions I think asynchronous reality makes a lot of sense*" (P13). Only P8 disagreed with that, stating "*I felt more productive getting the information while I was working.*" P15 and P25 specifically mentioned that they think they would have been more productive without the VR headset, but given the VR setting they preferred the asynchronous mode. Moreover, some participants stated that the synchronous interruptions made them feel irritated and stressed which they explicitly mentioned to not be the case for the asynchronous condition (Participants 1, 2, 7, 9, 11, 12, 18, 19). Several participants stated that they did not even consider the asynchronous interruptions to be interruptions (Participants 6, 8, 11, 12, 14, 16) with P12 specifically saying: "*I didn't feel interrupted at all, it actually was perfectly timed.*" Half of the participants saw asynchronous MR communication systems as a viable alternative for synchronous communication in workplaces (Participants 1-4, 10, 13-15, 17, 19, 21, 23, 24, 26), as long as it would only be used for conversations of instructional nature. The others stated that they would rather use it as an additional tool to aid communication at workplaces (Participants 7, 9, 11, 12, 20). Participants 1, 2, and 9 specifically expressed the concern that blocking all interruptions could not be ideal since urgent interruptions would be delayed as well: "*One consideration that might be important is how the system would deal with urgent interruptions. For example, if you had noise-cancelling headphones on and there was a fire alarm, but the alarm was not very loud in your office, you might miss that because you are so deeply focused.*" (P1) Overall, despite smaller concerns, all participants reacted very positively to the asynchronous communication system of the study.

In addition, we asked participants about the system design. P7 found the recording *creepy* and would have preferred an avatar over the point cloud. In contrast, P15 specifically mentioned that they like the point-based rendering. P12, 18, 24 were surprised that the recording did not bother them at all and that it felt natural. P19 appreciated the simple setup and how well it worked in the VR setting. P23 wished for more customization in terms of interruption handling. Customization of interruption handling as well as other technical and design factors are important aspects when discussing future prospects of such systems. We elaborate on those and other aspects in the next section.

# 6 Discussion, Limitations and Future Work

We have shown that MR work environments can bring many benefits to in-person interruptions that were previously limited to purely digital interruption handling. This includes retaining transient information connected to the interruption (instructions, explanations etc.) and even delaying the visual appearance of physical objects related to an interruption. Even though we were not able to prove a vast improvement in every aspect with regards to performance metrics, we found various subjective improvements that asynchronous co-located MR technologies provide This includes an improvement of the emotional state and a reduction of the perceived workload. Our results complement and partially corroborate findings about negative effects of interruptions found in previous research that investigated different metrics and technologies revolving around task interruption. For instance, Altmann et al. [2] have shown a negative effect on error rate with short interruptions, whereas our findings, which point towards a positive effect on *subjective* performance, can be seen as complementary. Previous works with similar goals mostly investigated interruptions in conventional desktop environments or specialized use cases like driving [50]. More generally, while we could not replicate results in terms of task performance [5, 11, 19], our results with regards to negative effects of interruptions on the emotional state are similar to previous literature [4]. In this sense, our findings are close to Mark et al.'s [44] study (simulating information work tasks) indicating that their interruptions were perceived as stressful while not hindering objective performance.

Within the scope of task delivery scenarios in physical space, we can conclude that some findings from previous literature on interruptions in desktop environments transfer to immersive MR office environments. This means that in some cases immersive physical-digital MR offices can leverage the positive effects of deferring interruptions even beyond the handling of *purely digital* interruptions. Physical interruption handling augments existing capabilities of immersive offices like practically limitless and flexible space for virtual screens and 3D contents and might even have positive effects on well-being analogous to the positive effects of batching smartphone notifications [24]. Potential long-term effects like this and many other open questions in the context of MR offices lead to various future research endeavours, which we discuss in the following.

We focused on interruptions comprised of *instructions* including delivery of task-related physical objects (e.g., piece of paper). There are still many other types of interruptions, for many of which synchronous communication is likely preferred (e.g., longer dialogues or situations in which the interruption only works in the context of the current task) and which require dedicated user studies. Relatedly, in our study, we pre-defined the moment for an interruption. We envision that, in an actual system deployment, the user can enter or leave the asynchronous mode manually. In that way, times when the user is willing to be interrupted can be even more efficiently exploited. Overall, an ideal MR system for workplaces would need to enable seamless transitions between synchronous and asynchronous communication.

There are still design questions that need to be answered before asynchronous MR systems can become feasible. We made the task interface and MR environment as familiar as possible. Concretely, the virtual environment and keyboard setup was designed to resemble current desktop environments, while still being perceived as immersive MR environment. While participants got used to the setup over time, there were some initial minor obstacles. The position of the webcam pointing at the keyboard and its resulting camera view led to some confusion during the study. Furthermore, participants tried to read the piece of paper by positioning it relative to their eyes (which would be the intuitive way to get the object closer or further away), but since the webcam was not head-mounted, the participants most often moved the object in an undesired direction or out of camera view. Despite such technical limitations, all participants were eventually able to intuit their way through the interface and the environment. While this was not the main focus of our study, this can be an indicator that MR workplaces can already become feasible within the near future.

As mentioned before, participants were exclusively interacting with task-related objects. However, embedding virtual entities in Real office environments also means that systems need to deal with potentially cluttered desks. Specifically, an envisioned asynchronous system will need to keep track of relevant objects, e.g., based on their causal relationships [22]. Besides the technical implementation, it also remains to be tested, how immersed users would make use of an asynchronous system in a cluttered environment.

Another aspect not to be underestimated when imagining a deployment of an asynchronous communication system is a potential uncanny valley effect, which is a particular problem for communication based on recorded videos as the recorded user cannot directly interact with and respond to verbal and non-verbal cues [64]. To avoid such effects, a viable solution would be to replace the communication partner with an avatar. Dubosc et al. [16] have shown that more anthropomorphic facial properties of an avatar appear to improve attractiveness which again improves task performance. However, key objects related to the task would always need to retain their appearance independent of the representation of the communicators.

This study specifically explored the perspective of the *recipient*, and not the *initiator* of the instructions. In an envisioned asynchronous system, an initiator can provide information and objects in-person no matter whether the recipient is available or not (focused, not present etc.), but there are still open questions with regards to naturalness and how to represent the recipient.

## 7 Conclusion

In this work, we conducted a study to find out whether asynchronous MR communication systems could be an appropriate alternative to synchronous communication in MR offices. We investigated the impact that deferred interruptions have on the performance, workflow, and mental state of a person. Our study particularly focused on the perspective of the immersed *recipient* of the spoken messages. The participants felt less stressed and frustrated when instructions were delivered asynchronously and reported an overall decreased perceived workload. Nevertheless, asynchronous MR communication systems are likely limited to occasions and places where the communication is primarily one-sided and where swift information flow is not a requirement. Asynchronous communication via MR technologies is not a replacement for real conversations, which cannot be surpassed in efficiency and sense of presence. Hence, asynchronous MR communication can rather be seen as an additional tool, e.g., for maintaining focus.

In sum, while an asynchronous communication is not a singular reason for using MR in workspaces and should certainly not replace synchronous communication, we have shown that asynchronous co-located communication as a type of interruption handling can be beneficial from a human factors perspective and can be an integral part of future immersive work environments.

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