Mixing and Matching: Instruction Conveyance for Collaborative Tasks Using Asymmetric Augmented Reality Setups

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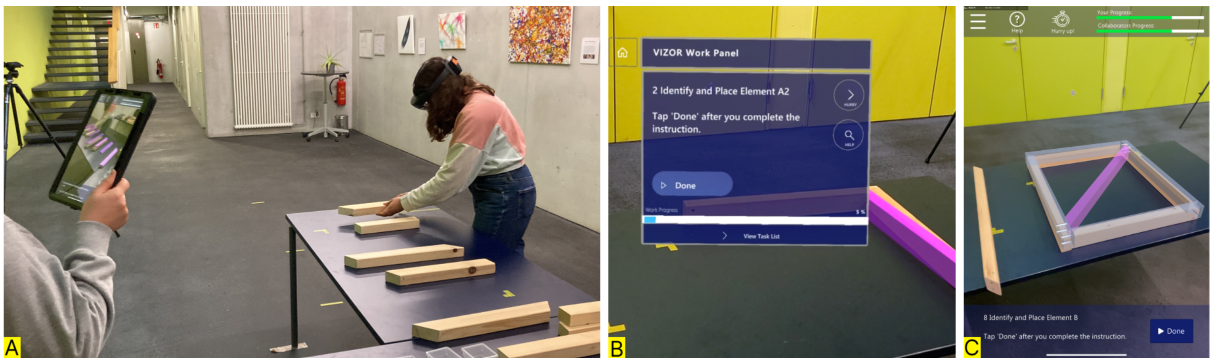

Figure 1: **A:** Collaborative solving of a task, utilizing two different AR interfaces **B:** View of the HMD interface **C:** View of the HHD interface

Abstract

Augmented Reality (AR) applications can provide support to users with task instructions in-situ. Among different AR display types used for these applications, head-mounted displays (HMDs) and handheld displays (HHDs) are popular solutions. Previous research has examined asymmetrical setups, i.e., two or more people using different types of devices at the same time. However, asymmetrical setups for physical tasks that require collaboration have been little investigated. Our work implements dyadic assembly and sorting tasks supported by simultaneously using an HHD and an HMD. We conducted a user study (N=20) to evaluate this setup. Participants rated both displays' usability similarly but showed a preference for HMD during both sorting and assembly tasks. While most participants agreed that they collaborated with their partners and the task was easier done in a team, less than half of HMD users in the sorting task agreed with the statement.

Index Terms: Augmented Reality, Collaboration, Data Visualization.

1 Introduction

Building and assembling based on instruction sets are familiar tasks for many of us from a young age. This ranges from solving puzzles where unique pieces are identified and placed in a target configuration to furniture assembly where a kit of parts are joined into a final object. In the field of Architecture, Engineering and Construction (AEC), assembly tasks are scaled up to larger and more complex components and connection types, requiring construction documentation and instructions. Because of this complexibility, research has also focused on how we can better support ergonomics and reduce mental workload for workers [7, 27, 5]

Information support for these assembly tasks can be provided through situated visualizations, where the instructions are displayed in-situ next to the physical objects [18]. Recent works have studied how such information can be used to support tasks, and there is evidence that connecting the data with physical world referents can be beneficial for users, supporting their decision-making process [20, 13] and reducing context switching [6]. Scenarios such as education [26, 24], health [15, 2] and navigation and guidance [1, 30, 12] were explored in the literature and benefited from the connection between digital content and physical referents. Either individually or in collaborative tasks, situated visualizations can be used both when users are working together in person or remotely. Various types of AR displays have been used across research and industry to facilitate such dynamic visualization of the instructions [3, 8, 19, 21], where users can easily interact with digital content while completing tasks.

The goal of our study is to understand the benefits and shortcomings of Head-Mounted and Hand-Held AR displays (HMDs and HHDs, respectively), and evaluate the usability of such setups for collaborative assembly tasks. Throughout this paper, we will refer to such a combination as an asymmetric setup. Previous work has compared similar scenarios [16] and concluded that although HMD instructions could lead to fewer errors and faster completion times, participants would rather promote HHD instructions, possibly due to higher familiarity and physical comfort. Our study aims to further explore these findings in collaborative assembly scenarios common in construction and better understand the differences between these display types.

Our research builds on previous work by Yang et al. [29], where the authors summarized open issues for future research in collaborative fabrication involving multiple humans and industrial robots in the AEC industry. Among the research questions identified, one important aspect was **how AR can support communication among teammates during collaborative task completion**.

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User feedback suggested that wearing the device led to insufficient eye contact with peers, headaches from prolonged use, and interference with glasses, which are issues also common across studies using AR headsets. Since this is a multidimensional question to answer, we decided to evaluate how users interact in an asymmetric scenario as a first step. Considering these factors, we selected an HHD device to explore how the execution of collaborative tasks may benefit from a mixed-device configuration. Our paper contributes implementing a collaboration scenario using an asymmetric setup of AR devices to support users completing two different tasks. We deployed a similar interface in two different AR interfaces, and present the results regarding the user experience and preferences when using an HMD compared to HHD. Participants showed a preference for using the HMD interface, and we discuss the main aspects that should be considered for each interface based on the feedback we collected.

2 Background and Related Work

In this section, we relate to prior work on applying AR for collaboration use cases, specifically instruction conveyance. In addition, we include references to commercial tools used in the AEC industry.

2.1 AR for Instruction Conveyance

Previous research has addressed how to convey task instructions via AR to a single user [14, 3, 16, 4]. Overall, situated instructions showed faster assembling times, lower error rates, and lower cognitive load compared to non-situated instructions [9]. However, a long-term study [8] on situated instructions at an industrial workplace showed that these benefits only apply to untrained workers in the learning phase. Once they were more familiar with the tasks, situated instructions slowed them down; the same applied to expert workers.

The way the immersive content is implemented also influences the performance of systems. Factors that potentially influence the results are the placement of the visualizations relative to the object of interest, the color and shape of the visualization as well as the light conditions of the surroundings [6].

2.2 Asymmetric Immersive Setups and Collaboration

Asymmetric collaboration is referred to as the usage of different AR or Virtual Reality (VR) devices by two or more people at the same time to complete a task [11]. The participants in the user study comparing asymmetric and symmetric collaboration in VR/AR showed high cooperation regardless of the visualization and interaction asymmetry. In our study, we have a comparatively smaller asymmetry with both participants using AR visualizations but through different displays.

Goepel and Crolla [10] conducted a workshop where multiple users collaboratively constructed a sculpture with the help of AR. The participants used both HHDs or HMDs to interactively guide them through the manufacturing process. This case study showcased the potential of employing AR technology in architecture but did not cover usability or other human factors between the AR devices.

Riedlinger et al. [25] compared an HHD with an HMD by having pairs of people performing collaborative building maintenance and design tasks. The HHD was preferred by most users for collaboration and discussion and perceived as more natural in its interaction since multiple people can share a screen. In addition, participants mentioned it was more suitable to get an overall impression of a bigger space. In STREAM [17] the authors combined two devices in a collaborative scenario, where the users viewed immersive content in an HMD and could have more freedom to manipulate the data using a tablet as an input device. Both users had access to both devices at the same time. More recently, Zhou et al. [31], explored the use of different AR devices to adjust light conditions in a room. The study simulated AR in a VR environment, given the higher degree of control. The authors explored which types of visualizations were preferred by the users and derived recommendations for designing such scenarios.

Our study addresses a few of the limitations observed in previous works such as the use of situated visualizations with AR in the real world and the assessment of the user experience during task completion. We also based the tasks on those used in prior research to study collaboration in timber construction [23] to improve the ecological validity of the study for the AEC industry.

2.3 AR in the AEC industry

With AR technology becoming more accessible, its application in the AEC industry has seen contributions from both research and industry. Several commercially available solutions provide AR instructions for assembly. Frontline by TeamViewer [1] supports a variety of industrial tasks such as assembly guidance (xMake), remote assistance, and inspection. Incon [2] utilizes vision-based tracking algorithms to detect and align digital content in construction and assembly tasks. Fologram provides tools to integrate AR in the popular 3D modeling environment Rhinoceros[3], which lowers the entry barrier for less experienced users to generate AR assembly guidance [4].

The use of these technologies has been reported in numerous research projects. For instance, AR interfaces can facilitate the assembly of novel structures otherwise infeasible using traditional paper documentation [10]. These interfaces have also been applied in collaborative assembly with both humans and robots [22], e.g., where AR HHD devices can support users in positioning instructions and registering the assembled elements to handle tolerance build-up.

Though AR has been deployed in various construction scenarios with different types of displays, how asymmetric setups can better support instruction conveyance and collaboration is still an open question. The study aims to shed light on this issue and support more diverse co-located collaboration setups for AEC tasks.

3 Methods

The following subsections present our system implementation and the user study design and procedure.

3.1 System Implementation

We implemented our AR interface on an HHD, namely the iPad Pro. The system extends the previous HMD implementation and an AR-based collaborative fabrication system, VIZOR [28].

3.1.1 Choosing the Device

The HMD interface was built using the Microsoft HoloLens 2 with the MRTK standard UI. For the HHD we used an iPad Pro (2020) due to its Lidar camera sensor and screen frame rate. We used Unity[5]2022 to develop both devices' applications.

3.1.2 Conveying Instructions

Both the HMD and HHD interfaces of our study convey instructions through text and situated visualizations. The text instruction is shown on a panel, and a virtual model corresponding to the task is rendered on a table. When the user is finished with a task step, they tap on a button to advance to the next step. For sorting, the task was

[1]https://www.teamviewer.com/en/products/frontline/
[2]https://incon.ai/
[3]https://www.rhino3d.com/
[4]https://fologram.com/
[5]https://unity.com/

to order the elements according to the illustration for which the sequence did not matter. In this case, the instruction and model were provided in a single step. In assembly, we provided step-by-step instructions to guide the participants through the assembly sequence. With each advancing step, the virtual model grows by an added object of interest. Figure 1 and Figure 2 A and C illustrate both device's interfaces.

3.1.3 Facilitating Collaboration

First, we visualize the partner's progress in the user interface to facilitate synchronization. The progress bars in the HHD interface visualize the progress of the user and their partner. The HMD interface previously only showed the user's progress and we extended it by showing a visual cue whenever the partner's progress was ahead. A second feature we included was a panel for sending pre-defined short messages with the push of a button since verbal communication can be impaired, for instance, when working in a loud environment. Having a selection of common messages to exchange among co-workers could be an alternative to direct talking or gestures. Our short messages included a button that indicates the sender needs help and another one asking the partner to hurry.

3.2 User Study

3.2.1 Experimental Design

We designed a collaborative scenario with assembly and sorting tasks. One team member performed the task with the HHD, while the other one did it with the HMD. After completing both tasks, the participants switched devices and did them again. Each time, they had a different set of timber sticks to work with for the assembly task. In sorting, they used the same set of sticks twice but had a different sorting order in each turn. We counterbalanced the order in which they started with each task, and they were free to choose which device they wanted to start with.

3.2.2 Experimental Setup

The AR devices we used in the experiment were an Apple iPad Pro (2020) and a Microsoft HoloLens 2. To run the back end of the AR clients, we used a standard consumer laptop. We placed the relevant material for the tasks on two tables arranged in a T-shape. For the sorting tasks, the used material consisted of several timber sticks, varying in lengths and angled ends. For the assembly tasks, we used different timber sticks that can be assembled with screws into a simple truss structure. We additionally provided the participants an electric screwdriver and different kinds of screws placed in their respective boxes. The experiment setup can be seen in figure 1 and 2.

3.2.3 Tasks

We adopted tasks that have been used in prior research to study collaboration in timber construction [23]. The tasks involved (1) the assembly of a simple timber structure and (2) the sorting of different timber slats with different shapes. We implemented these two tasks, keeping in mind that they are simple enough to be generalized to more complex tasks that are present in more complex scenarios of industrial environments.

- Sorting: The task consisted of sorting twelve wooden sticks with different lengths and cut at different angles. The order of the sticks was visualized through both AR interfaces by displaying virtual sticks on the table. The wider field of view of the HHD device could be utilized by one user to guide the HMD user from afar, as shown in 1. The participants were given a singular instruction, which told them to sort the sticks according to the visualization. Figures 2 A and B show the assembly structure and order of the sorting task.
- Assembly: Here participants were given another set of wooden sticks with holes in them for placing screws. In total, we provided ten instruction steps consisting of identifying objects, picking & placing and screwing tasks. The instructions depended on the device type used by the participants. Due to its hand-free interaction, we assigned instructions that consisted of screwing to the HMD user. Both participants had to identify the correct sticks to assemble, while picking screws was only assigned to the HHD user. To add complexity to the task, we included different colored screws, requiring the HHD user to carefully read the instruction and pick the correct type and amount of screws.

3.2.4 Measurements

We asked the participants to fill out a survey with both the System Usability Scale and NASA Task Load Index items. Regarding the participant's experience and collaboration, we collected feedback through the following questions (on a scale of 1 to 5): *Q1 - The task was easy to solve*, *Q2 - The task was easier with a partner*, and *Q3 - I collaborated (discussion, gestures, etc.) with my partner*.

For qualitative data, we posed two open-ended questions on their device preference and what they liked or disliked about the study. Finally, we tracked the time that the participants needed to complete each task.

3.2.5 Participants

20 people participated in our study in total between the ages of 18 and 34 years old. 13 were male, 6 were female, and 1 preferred not to disclose their gender. We invited pairs of participants to do the study together. When signing up, the participants selected possible time slots to take part in the study. We then assigned the time slots to the first two people who signed up for them. We did not inquire the participant pairs whether they knew each other prior to the study.

3.3 Procedure

We started by asking each of the participants to go through the instructions provided by the Microsoft Tips app for the HoloLens, which introduces the main interaction commands of the headset. After that, they were assigned to an alias to ensure the data would stay anonymous. Then, we explained the tasks and showed them the timber materials used for each task. During the task explanation, we showed them a few screenshots of the device UIs, how they should interact with them, and that they would switch between devices. After completing each task, the participants completed the questionnaires regarding the task load, SUS and general questions. By the end of the study, they were asked to answer questions about their experience with building furniture or similar objects, whether they do these activities together with other people, how much they usually rely on instruction manuals, and demographic information.

4 Results

In the following we present the results of the user study that we obtained through the questionnaires. Besides the questions on usability, mental load and collaboration behavior, we asked them about prior AR experience. 14 participants reported little or no AR experience and 2 considered themselves as experts.

4.1 System Usability

For assembly, we have a mean SUS score of 76 for HMD ($SD = 13.41$) and 74 for HHD ($SD = 14.5$) with no significant difference ($p = 0.26, r = 0.14$). For sorting, HMD has a mean score of 78 ($SD = 13.96$) and HHD scored 69 ($SD = 17.63$) with a significant difference ($p = 0.04, r = 0.45$) between the devices for sorting tasks.

Figure 2: A: Interface of the HHD and assembly task structure. B: Timber sticks positioned in the sorting task. C: HHD interface showing one of the predefined messages from partner.

A previous exploratory study where an earlier version of VIZOR was used [29], yielded similar results with a mean SUS score of 73.5 ($SD = 12.2$). Despite a different task environment, the main differences between the HMD interfaces are the short-message buttons and progress bars for visualizing the collaborator's state. Figure 3 showcases the SUS scores for each device and task combination.

4.2 Task Performance and Workload

For each of the NASA TLX questions, the users could mark their workload on a scale of 1 to 20. To better visualize the data, we categorized it in our figures as: *Low* (1-5), *Medium Low* (6-10), *Medium High* (11-15) and *High* (16-20).

Figure 3 shows the overview of the NASA TLX results for both conditions. In the assembly task, the values are almost identical in a positive way: 80% of the participants participants reported a *High* score for their performance. The other categories were mostly (>75%) in the *Low* or *Medium Low* ends. For sorting tasks, 75% of the participants indicated their Mental and Physical demands to be *Low* or *Medium Low* in the HHD condition, compared to 100% and 95%, respectively with the HMD one. Since the results for both conditions were lower, we interpret them as a positive indication that the task was not too straining for the users. In addition, we also think the consistency between conditions indicates that users could complete the tasks easily with both devices.

4.3 Collaboration between Participants

For sorting tasks with the HHD, 13 participants found the task easy to solve, compared to all 20 agreeing with the statement in the HMD case. 15 participants felt that the tasks were easier to solve with a partner using HHD, while only 9 participants using an HMD agreed with the statement. 4 participants using the HHD and 3 using the HMD felt that they did not collaborate at all with their partners when they did sorting tasks.

Though participants reported collaborating less during sorting tasks compared to assembly, over half of the participants strongly agreed that they collaborated in assembly tasks, regardless of the instruction interface. No participants strongly disagreed on whether they collaborated in assembly tasks. The participants' increased collaboration behavior for assembly tasks might be due to the higher complexity of the task itself which increased the need for discussion. The results for the task feedback items are visualized in Figure 4. After completing all the tasks, we asked the participants about their collaboration preferences during similar assembly activities, like building furniture at home. 11 people expressed their preference to work together with 1 more person, while 8 people generally prefer to work alone. One person reported that they had never done similar tasks before the study.

4.4 Qualitative Feedback

After completing all tasks, we asked our participants whether they preferred the HMD or HHD interface, the reasons for their preference, and what they liked or disliked about their overall experience in the user study.

14 participants stated that they preferred to work with the HMD interface in both tasks. 5 participants expressed their preference towards the HHD, while 1 said they liked both interfaces for their own reasons. The main reason for the HMD preference is the **hands-free handling** — *"with the iPad you always had something in your hands and wasn't able to build and check at the same time."*

One participant wrote *"I preferred the iPad over HoloLens, because it was harder to be in glasses"*, which relates to personal **ergonomic preferences**. We did not receive as much feedback regarding physical discomfort as expected, with only two participants commenting on physical discomfort regarding HMDs.

However, some commented on comfort regarding interaction, with a preference towards HHD: *"I liked trying the HoloLens even if I did not find it too comfortable to use, it was not so simple to click the buttons on the interface. I liked the tablet system instead"*.

Indeed, many of our participants struggled when pressing buttons on the HMD interface: *"I would prefer the iPad because it's comparatively easier to use with fixed buttons"*.

5 Conclusion and Discussion

Our study analyzed collaborative task completion using an asymmetric AR device setup, with the aim of making co-located collaborative AR more diverse.

We find that most users prefer HMD to HHD in both assembly and sorting task conditions. However, user preferences are also somewhat personal, where the limitations with one device bothered some users but not others. HHD was previously reported to

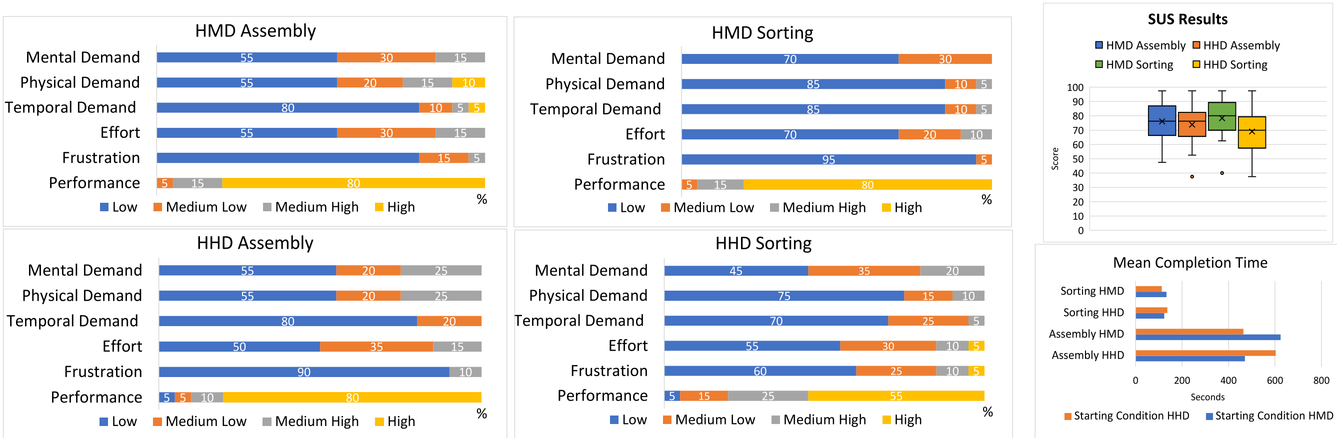

Figure 3: NASA TLX, SUS, and Task Completion results for all device and task combinations.

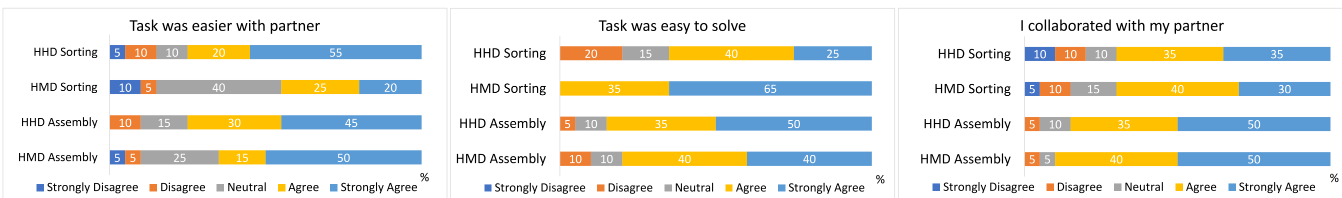

Figure 4: Task feedback results based on the questions we asked participants, on a scale of 1 to 5

be preferred compared to HMD for gaining an overall view of the workspace [25], but this preference is not applicable when the task requires the user to be simultaneously within arms reach from the manipulated elements.

As a first step, we have implemented two tasks, which are commonly found in use cases of the AEC industry, and they were then successfully completed by participants using both devices combined. According to the feedback of the participants, we could attest that these are tasks that they would like to collaborate with somebody else to do, in spite of the AR support, therefore being good examples for an evaluation.

Our results show that there was a preference for HMDs, but both AR displays were generally well accepted. In addition, our interface also facilitated the understanding of the progress of the task by adding a bar that informed the other participants' progress on the same task. We believe that using AR to improve this communication and awareness of the collaborations is a crucial next step. Our findings highlight the need for more investigation towards the task nature and collaboration setup needed for each use case. We observed that with a higher task complexity, a higher collaboration level was needed, and in the future we would like to investigate how the usage of situated visualizations can support users further with their goal. Another important aspect is that our tasks did not take very long to be completed, and the impact that HMDs have on long usage periods needs to be better understood. This is a point that could influence the user's preference on the device.

5.1 Limitations

A few limitations of the study are outlined below.

- **Task design**: We took inspiration for our tasks based on past use cases and related studies. Naturally, using tasks that rely on participants grabbing objects can lead to a preference for hands-free devices, which in our case can explain their preference for the HMD condition. Different tasks would have changed the results and the combination of different user roles in the same task might also impact the outcomes.

- **Tracking**: The tracking accuracy was lacking and may have impacted the usability rating. Since we wanted to keep consistency between AR setups for the devices, we opted for using QR codes as markers to place the digital content for both devices. For iPad, QR codes are not the best alternative since they have a lower registration quality. This problem can be overcome by choosing markers that work better with both devices or using third-party libraries.

- **Measurements**: The collaboration process can be investigated in more detail using objective measurements, video analysis or further questionnaires about perceived collaboration degrees. Our current data is limited to subjective reports due to the number of questions already present and time constraints in the study duration,

5.2 Future Work

As our study was meant as a first step towards better understanding asymmetric AR setups, there are paths to explore in future studies.

- **Communication**: We believe that AR has great potential to improve communication between collaborators. For example, providing a better overview of one's partner's current activities and upcoming tasks in a visually succinct manner would be one of the follow-up steps. One could also consider incorporating more situated visualizations in the scenario, which can convey information directly connected to the participants' physical locations in addition to the task-oriented interface.

- **User roles and tasks**: Since different devices have different interaction patterns, we believe it will be interesting to investigate and characterize which devices are more suited to specific tasks. Along these lines, it is possible to have different roles for users working together on the same task, so associating certain devices to certain tasks can make it easier to define user's roles accordingly. For example, in monitoring situations where an overview of the work area and collaborators is more relevant, projectors or mobile devices might be more suitable. In contrast, manual tasks would be a better fit for HMDs. It is important to highlight that with more dimensions, the evaluation also gets more complex, which is why we decided to start with this simplified setup as a first step.

ACKNOWLEDGMENTS

This work was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC 2120/1 – 390831618 and BBSR as Zukunft Bau Project "MRK II Projektnr. 10.08.18.7-22.22". The authors thank the International Max Planck Research School for Intelligent Systems (IMPRS-IS) for supporting Aimée Sousa Calepso.

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