Virtual Reality Simulation for Multimodal and Ubiquitous System Deployment

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Abstract: Multimodal IoT-based Systems (MIBS) are ubiquitous systems that use various connected devices as interfaces of interaction. However, configuring and testing MIBS to ensure they correctly work in one's own environment is still challenging for most users: the trial and error process in situ is a tedious and time-consuming method. In this paper, we aim to simplify the installation process of MIBS. Thus, we propose a new VR methodology and a tool that allow the configuration and evaluation of MIBS thanks to realistic simulation. In our approach, users can easily test various devices, devices locations, and interaction techniques without prior knowledge or dependence on the environment and devices availability. Contrary to on-the-field experiments, there is no need to access the real environment and all the desired connected devices. Moreover, our solution includes feedback features to better understand and assess devices interactive capabilities according to their locations. Users can also easily create, collect and share their configurations and feedback to improve the MIBS, and to help its installation in the real environment. To demonstrate the relevance of our VR-based methodology, we compared it in a smart home with a tool following the same configuration process but on a desktop setup and with real devices. We show that users reached comparable configurations in VR and on-the-field experiments, but the whole configuration and evaluation process was performed faster in VR.

1 INTRODUCTION

In recent years, the spread of the Internet of Things (IoT) has brought a lot of connected devices into our surroundings. These sensors and actuators that surround us simplify our interactions with the environments we live in, such as homes, offices, and factories. Moreover, they can provide a diversity of modalities (e.g. vocal, visual) at a larger scale, which renews the interest in multimodal interactions (Pruvost, 2013; Peters et al., 2016). More specifically, they allow the development of ubiquitous systems (Weiser, 1991) such as **M**ultimodal **I**oT-**B**ased **S**ystems (MIBS) (Poirier et al., 2022) that use connected devices as medium of interactions. While there are already instances of such systems in the literature, such as the ubicomp home assistant presented in (Almeida et al., 2019), the interactive museum game in (Manca and Paternò, 2016) or the supermarket shopping application in (Ghiani et al., 2015), MIBS are not currently available off-the-shelf because it is still difficult for MIBS administrators (i.e. people in charge of the MIBS deployment, generally building administrators or end-users) to easily and fully adapt these systems to their own ubicomp environments.

Indeed, the usability of a MIBS depends on the targeted environment topologies, on the interaction techniques alternatives, on the selected connected devices, and on the end-user profiles (Pittarello and Celentano, 2007). These parameters are specific to each environment and end-users, they cannot be fully anticipated beforehand. Thus, MIBS administrators need to test various configurations (i.e. interaction techniques, connected devices and their locations in an environment), resorting to installation tools (Tavakolizadeh et al., 2019) and documentations (Miclaus et al., 2014) to guide them, until they find a satisfactory configuration. requires technical knowledge, takes time, and the feedback coming from IoT-based systems could be difficult to understand for a MIBS administrator. To allow non-technical users to configure and test interactive applications in ubicomp environments, recent work has investigated the use

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of Virtual Reality (VR) and Augmented reality (AR) tools (Suzuki et al., 2019; Lacoche and Villain, 2022). This way, users can have a better spatial understanding of the configuration process, but there is no support for the deployment of more elaborated and longer interactions that can come across in MIBS.

This is why we propose a new VR-based methodology and a tool for MIBS administrators to configure and evaluate MIBS in realistic modeled environments before deployment. MIBS administrators are immersed in a digital twin (Grieves and Vickers, 2017) of the target environment. Such a digital twin includes information about the geometry of the target environments as well as information on the characteristics and behaviours of target connected devices. Thus, the administrators can observe and move similarly to reality during the configuration and the test process. The proposed tool facilitates the deployment process for MIBS administrators. First, it allows MIBS administrators to select services, interaction techniques and to manipulate simulated devices simply and effortlessly. Second, it is possible to evaluate in VR the configured services to provide a similar experience than in reality, without needing any real device or access to the real environment. Thus, our choice of VR over AR allows to support the use cases where buildings are not available. Finally, MIBS administrators are able to provide feedback to MIBS producers (e.g. developers or designers) or to generate data facilitating the installation of the configured services in a real environment. A study demonstrates that our methodology is better suited for MIBS configuration and testing than on-the-field (OTF) experiments (i.e. test the system in the actual space with real devices).

In section 2 we present a review of the related work. Then, in section 3 we introduce the MIBS Configuration and Evaluation methodology, the VR tool we created, followed by a presentation of the study and a discussion of the results in section 5. Finally, we conclude and present perspectives for future work.

2 RELATED WORK

The deployment of an ubiquitous system in one's own environment is an important step in this system life cycle, and is in most cases up to its administrator (Beckmann et al., 2004). To assist him, most of the approaches provide tools to facilitate the systems configuration and test processes. These tools can be classified into three categories. First, the most common ones are the 2D graphical desktop tools that support the association process between the devices and the system. Second, some desktop tools also include features to improve the visualisation and manipulation of spatial information. Third, more recent work harness the immersive potential of VR and AR to facilitate the deployment of IoT services.

2.1 Tools for Multimodal Interactions

ICON (Dragicevic and Fekete, 2001) is a developer tool to configure multimodal systems. Users graphically assemble software components to create a given service, or use preexisting ones and modify them. It provides a separation between a service and the devices capabilities, but requires technical knowledge to create functional interaction techniques, and doesn't include usability evaluation features. The dynamic customization tool in (Manca and Paternò, 2016) enables users to distribute different parts of the interface across devices. They can also modify the distribution of the interface while testing the system. However, interaction techniques cannot be selected independently from the available devices. With MIBO IDE (Peters et al., 2016), interaction techniques can be assembled from easy-to-understand components without programming skills. Here, devices are preprocessed to only show the modalities they can offer, and the configurations are compared to find possible conflicts. Moreover, this tool displays the events generated by the system at runtime. All these graphical tools are easy-to-use and support the selection of devices and interaction techniques for a desired service. Some tools even provide support to evaluate the configurations. However, they do not handle the spatial distribution of devices in the environment, which is essential in MIBS (Pittarello and Celentano, 2007). Indeed, multimodal interactions can require the cooperation of multiple modalities to work properly, and these modalities are provided by different devices placed at different locations in MIBS.

2.2 Tools for Spatialized Interactions

Biehl & Bailey (Biehl and Bailey, 2006) provide a tool to associate applications to situated displays and tablets using a top view of the modeled room. Users have a better understanding and performance with their spatial representation than with a simpler tool without spatial information. However, this tool is limited to the configuration process. To help ergonomists configure and evaluate MIBS, Pruvost proposed three tools: the ontology editor "Describe" to model the environment, the rule editor "Behave" to define the system behaviour, and the simulation tool "Simulate" (Pruvost, 2013). The latter is a tool to test MIBS behaviours with different sets and locations of simulated devices and people. Devices and people are represented as icons while the environment is represented as multiple schematic areas. Their evaluation approach with simulation has the benefit of evaluating a larger panel of configuration at low development cost. Nevertheless, this approach requires knowledge on ontologies and logical rules to configure MIBS. Recent work on the notion of proxemics (Chaoui et al., 2022) provide partial support to configure and evaluate MIBS. Proxemics is a paradigm to describe relations between entities (e.g. devices, users, furniture). For example, the distance and motion of a tablet relative to a camera could be used to define the behaviour of these devices. The Proximity toolkit (Marquardt et al., 2011) is a monitoring tool built on this paradigm to better grasp the link between the system behaviour and the locations of the devices and users. The graphical tool in (Ghiani et al., 2015) provides a simpler vocabulary for the proxemics (e.g. "near to" or "when user is moving") to adapt the distributed interface to the entities proxemics. Although these tools support spatialized interactions, users only have access to 2D representations of environments or textual information during the configuration process. Having a 3D representation can benefit to this process as some information cannot be visualized in 2D, or conceptualized from textual information only. For example, when configuring an interaction with cameras, one need to be careful about their horizontal and vertical view angles, as well as the minimal and maximal distances required to work properly.

2.3 Immersive Tools

AR and VR technologies have brought new possibilities in 3D representations, immersion, and more specifically in the configuration and interaction with connected devices. Indeed, MIBS can be configured and tested at scale one in a real environment (AR) or in its digital twin (VR) when the real environment is unavailable (i.e. in construction, renovated, too far away or already in use). For instance, ExProtoVAR (Pfeiffer and Pfeiffer-Leßmann, 2018) provides a methodology to prototype from 360 panorama pictures a Mixed Reality (MR) interactive system interacting with connected devices. The support of spatialized and situational interfaces, as well as the annotation and recording features, facilitate the creation and sharing of new designs by the system producers. Suzuki et al. (Suzuki et al., 2019) proposed the AR tool ReallifeEngine where the devices can be linked through visual programming interfaces. Thus, it is possible to create automation scenarios without technical knowledge while considering the device in the real environment. The pipeline introduced in (Lacoche et al., 2019) also provides support for the management of connected devices. It includes the creation of the environment digital twin with AR and VR. Moreover, the devices digital twins can simulate realistic behaviours, thus the system can be tested in VR independently of the real environment. In addition, Lacoche et al. (Lacoche and Villain, 2022) introduced a VR authoring tool that can help non-technical users adapt the interactive content elements in AR applications depending on information collected by connected devices. Another use of VR to configure systems is the virtual commissioning (VC) for the industry 4.0 (Lechler et al., 2019). The VC consists in the observation and validation of automation systems behaviour through hardware and software simulation, and it could be extended to interactive systems. For instance, Metzner et al. (Metzner et al., 2020) present a method to integrate a human operator to test programmable logic controllers (PLC). Although it is geared towards PLC producers and their business partners during production, it provides an intuitive and realistic device testing method. AR and VR are powerful technologies to convert the logical representation of interactive systems in intuitive and easy-to-visualize information. However, the existing tools are limited to MR services or IoT automation, thus providing insufficient support for the management of more complex and user-centered as multimodal interactive systems.

3 MCEV METHODOLOGY AND TOOL

There is currently no tool that fully supports the configuration and evaluation of MIBS. Thus, we propose MCEV: a **M**IBS **C**onfiguration and **E**valuation in **V**R methodology and tool to help MIBS administrators efficiently configure and test MIBS during the installation process in various environments. MCEV supports the selection of a MIBS context of use (i.e. environment, devices, services and interaction techniques), as well as MIBS simulations for immersive testings. Moreover, MCEV provides several feedback functionalities to share the configurations and evaluation results.

Ergonomists could also apply the MCEV methodology to evaluate MIBS during their production, similarly to the simulation methodology in (Loor et al., 2006). The five steps of our methodology and our tool interface are detailed in the next sections.

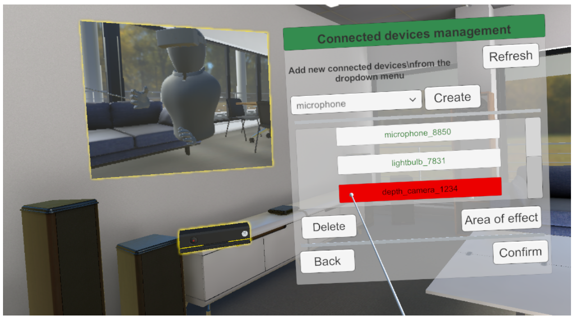


Figure 1: Device management menu.

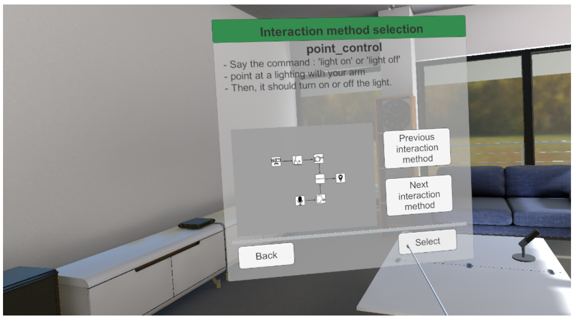


Figure 2: Interaction technique selection menu.

3.1 Environment Selection

First, MIBS administrators import their environments and select one at launch time. These environments could be sandbox environments such as simplistic environments or demo environments provided by the MIBS producers, or environments generated from the digital twins of the target physical environment. The creation of digital twins of devices and environments could be seen as a constraint but we believe this is not an obstacle nowadays: modern buildings are often described in Building Information Models (BIM), and recent tools such as the AR capture tool proposed in (Lacoche et al., 2019) can simplify this process. Therefore, MIBS administrators can configure and test MIBS in multiple and possibly huge virtual environments without delay, even if the real environments are unavailable. To navigate in these virtual environment, we provide a classic navigation feature consisting in pointing at a desired position to instantly move there.

In our evaluation introduced in Section 5, the digital twin was created from the model file (BIM) of the building and then fine-tuned by a 3D graphic designer. Nevertheless, digital twins of existing and available environments could also be obtained with capture tools such as (Soedji et al., 2020).

3.2 Connected Devices Management

To prospect changes in a real environment in preparation for a MIBS, the MCEV tool enables MIBS administrators to instantiate simulated devices (e.g. thermometer, connected speaker) in addition to those already included in the 3D environments (see Figure 1). These simulated devices are composed of 3D representations and scripted behaviours that reproduce the behaviour of the real devices. For example, the Kinect in Figure 1 has the same field of view than a real Kinect. Each device can also be moved or rotated by grabbing or selecting it with a ray.

Moreover, the MCEV tool enables MIBS administrators to observe visually or orally (when it makes sense) the *aura* (Benford and Fahlén, 1993) of connected devices, which are the areas in which they can sense or be sensed, to help with the identification and placement of these devices. For example, a MIBS administrator can place a camera in front of chairs to observe what it can see with its aura, as illustrated in Figure 3. Representing these auras enables MIBS administrators to rapidly and intuitively understand the impact of a device location on its performance, and find more easily a satisfactory location. Currently, our tool includes several device models with their *auras* that correspond to the real devices in our possession and it can be extended to any other device.

3.3 Selection of Services and Associated Interaction Techniques and Devices

The third step consists in selecting for each service to configure an associated interaction technique and devices that provide the necessary modalities.

For each service they want to configure, the MIBS administrator selects an interaction technique. Interaction techniques are described and are illustrated by a graphical representation of the associated software component chains. For example, in Figure 2 the user selected an interaction technique using a vocal command and a pointing gesture to turn on a pointed light bulb. Thus, the MIBS administrator doesn't need technical knowledge to understand how to test a configuration, but can obtain technical details by clicking on the different icons representing the component. The MIBS administrator can also rapidly determine what are the necessary modalities needed for the interaction just by looking the extremities of the chains. These interaction chains can be developed with one of the graphical component composition tool for multimodal systems, such as SKEMMI (Lawson et al., 2010). Here, the MCEV tool imports files describing possible interaction chains for each service, and provides simplified versions of these chains to the MIBS administrator for better readability.

Then, for each required modality, the MIBS administrator selects which devices to use. Each required modality can be associated to multiple devices, either from the list in a 2D interface, or directly by pointing at the devices. The list of devices the MIBS administrator can associate to an interaction technique is limited to the devices that can provide one of the desired modalities. To help understand the link between the two methods, the MIBS administrator can highlight each device and its identifier in the list. Therefore, the MIBS administrator can select devices intuitively by directly pointing at them. Moreover, the MIBS administrator also has a centralized view of the associations that simplify configuration modification and multiple device selection.

The configuration features in our tool are accessed through 2D user interfaces positioned in the 3D environment. We provide a classic 3D ray-based selection and manipulation technique to interact with these user interfaces and with the devices (see Figure 1).

3.4 MIBS Evaluation

Then, MIBS administrators can test the service to check the quality of experience offered by their configurations.

To do so, the MCEV tool relies on an execution engine to run the configured services. The execution engine is inspired by the state-of-the-art component-based architectures such as the AM4I architecture (Almeida et al., 2019) for their modular approach, ease of use and context awareness.

Then the simulated sensors generate information and the actuators act accordingly to the commands received from the system. Like in the virtual commissioning approaches in VR, the devices behaviours included in the device models are based on the real devices sensing and acting capabilities. Therefore, the MIBS administrator can interact in VR as they would do in OTF experiments.

During the test, the MIBS administrator can use a console to find the received events from the devices, the services, and the processing components of the interaction techniques. Thus, it provides more insights on the origin of a problem. This console is attached to the non-dominant hand, and can be collapsed.

3.5 Collaborative Review

Once a MIBS is tested, either a configuration is satisfactory and have to be deployed in the real environment, or there is a problem with the services, devices or environment that may require providing an explanation of the problematic context to the MIBS producers. To support both of these situations, the MCEV tool incorporates three collaborative features.

Figure 3: The *auras* of a camera (Kinect 2).

First, MIBS administrators can write located and time-stamped notes to describe the overall configuration (e.g. advice or warnings when installing a configuration), or during a test to notify about a specific situation. Information about the current environment, such as device positions, service state, and note position are automatically saved in each note. Moreover, the notes can be attached to devices or simply placed at a specific position in the tested environment. Thus, MIBS administrators can easily provide descriptive feedbacks to MIBS producers.

Second, MIBS administrators can record and replay their actions in the tested environments. Thus, they can check the impact of the MIBS use from an external point of view. For example, the inconvenience of vocal commands for other coworkers could be more easily noticed this way. Moreover, the recorded actions could be reused to test minor changes (e.g. changing the microphone model doesn't impact the interaction process) effortlessly.

Finally, MIBS administrators can produce 2D views of their configurations to help the ones in charge of the deployment in the real environment. Indeed, they can take screenshots from any location or angle in the environment, and automatically generate a 2D top-view map of the entire space with devices locations marked. The screenshots also display the localized notes that can be clicked to read them.

In addition, the notes, devices, and configurations created can be saved in configuration files and can be loaded to start from a preconfigured MIBS. Therefore, alternative configurations for each environment can be easily shared.

4 A 2D DESKTOP TOOL FOR OTF AND MCEV COMPARISON

To evaluate the MCEV tool (see section 5), we needed a graphical tool comparable to our tool that supports OTF experiments on MIBS. As the existing graphical tools only provide limited support (e.g. devices position can't be managed with the MIBO IDE (Peters et al., 2016), and the Proximity tool (Marquardt et al., 2011) only support the test process), we developed a desktop tool for OTF experiments that supports the configuration and test of spatialized and multimodal interactions. To ensure a similar setup than in VR, the desktop tool follows the same configuration process as the MCEV tool, with an almost identical 2D interface. Yet, there are notable differences between the MCEV and desktop tools features.

First, most connected devices can't know by themselves their locations in the environment, and there is no universal and automatic method to locate every connected device (Brudy et al., 2019). Therefore, devices locations are manually indicated with the desktop tool. It provides a 2D map generated from the digital twin of the environment, as illustrated in Figure 4. On this map, the iconical representations of the added devices can be moved and rotated to match the real devices positions. Like with the 2D configuration tools (chapter 2), this manual position tracking method ignores the height and two degrees of freedom in rotation. These dimensions were not used in our scenario so the positioning features capabilities of the desktop tool were sufficient for the experiment.

Second, devices in our MCEV tool can be highlighted to identify them from their identifiers, but this feature cannot be directly used in the OTF experiment with the 2D tool. However, sensors feedbacks are observable, and actuators can behave in a noticeable way. Thus, for each device in our experiment, we implemented a specific behaviour that the desktop tool was able to initiate when an identification was needed (e.g. camera feedback, light blinking). This feature was added to provide a fair and reasonable counterpart to the highlight feature of the MCEV tool.

Third, the devices *auras* in the desktop tool are represented by their 2D views. 3D visualizations such as in (Marquardt et al., 2011) were also considered, but they require to use additional tracking devices, which would create too much of a difference between an experiment OTF and in VR. Thus, we integrated a functionality to display or hide the *aura* of each device (e.g. the *aura* of a Kinect in Figure 4).

Finally, participants could associate devices by selecting the icons on the 2D map. Thus, the association process is based on a spatialized *Point and click* technique like for the method in VR.

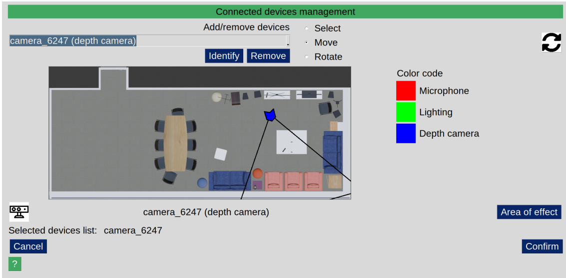


Figure 4: Devices management in the desktop tool. Participants identify the available devices and place them on the top view representation of the room. The black lines represent the border of the Kinect *aura*.

5 EVALUATION OF MCEV

First, we want to determine if our MCEV tool could help to configure and test MIBS faster than with the desktop tool in OTF experiments, without degrading the result. Second, we want to assess the cognitive load and ease of use of our MCEV methodology compared to OTF experiments. Indeed, even if most people are more used to mouse-keyboard interactions, we believe that VR can provide a more natural and efficient way to configure MIBS thanks to 3D interactions and navigation at scale one.

5.1 Experimental Context

To compare our MCEV methodology with OTF experiments, we asked participants to configure and test a light management service with both methodologies. As illustrated in Figures 5 and 5, the environment in VR was the same than in the OTF experiment.

5.1.1 The Light Management Scenarios

Our requirement for the experiment was to provide a scenario that showcases the use of multimodal interactions where the location of at least one connected device has an impact on the result. Moreover, some connected devices are difficult to install (e.g. power supply, wall mount, narrow *aura*). Thus, we wanted to use one such device. We avoided complex multimodal interactions as they can be difficult to use at first for most users, and as providing many modality alternatives is a repetitive task which is unnecessary for an experiment. Therefore, participants had to configure in VR and OTF a simple light management service, which covers a use case suitable to various environments (e.g. houses, offices).

This service consists in using vocal commands and gestures to control two connected lightbulbs placed at the same spots in the real environment and in VR (see Figure 5). To represent use cases in which some connected devices positions were already set and unchangeable, the lightbulbs were already positioned and could not be moved. Only two modalities in input (vocal and gestural) and one in output (luminosity) were possible to provide multimodal interaction without unnecessary repetitions in the configuration process. Participants had to use a microphone and a depth camera for the vocal and gestures commands. In the VR experiment, both devices had to be instantiated and placed. In the real environment they were in the room but purposely placed in wrong positions (see Figure 8), both devices were connected by USB to a laptop that ran the desktop tool, and the camera was fixed to a professional tripod adjustable in angle and height. The depth camera was used as an example of device that is difficult to install.

In addition to these devices that needed to be used during the experiment, other devices were available. Indeed, we wanted to recreate a scenario where connected devices from outside of the considered environment are available and detected. Thus, one lightbulb and one microphone were simulated in both experiments and were visible in the device identifiers list, but the participants couldn't find these devices around them.

To facilitate the comparison of devices positioning, the interaction space was limited to a specific area: participants were asked to configure the light management service in order to be used from a specific location (seated on any of the three beige chairs shown in Figure 5), with these techniques:

T1: control of the lighting with just the vocal command "light" to turn ON or OFF the lightings

T2: control of the lighting with a pointing gesture and a vocal command where the user needs to command orally to “turn on” or “turn off” a specific light by pointing at it.

T3: control of the lighting with a vocal command as a trigger to start or stop and considering the hand position to change the lightings intensity.

T1 was a monomodal interaction technique to learn the configuration process while participants tested T2 and T3 with both tools.

To provide similar conditions between the VR and OTF experiment, the VR environment was a high-fidelity replication of the real environment, which was a meeting room dedicated to user experiments that replicates a living room. In the VR environment, participants were embodied by a body composed of two hands and a body (see camera feedback in Figure 1). This body representation aimed to help participants situate themselves when they use the camera feedback, similarly to the real camera feedback.

5.1.2 Procedure

Participants had to experiment with both tools successively. They started with an explanation of the experimentation procedure. Then, for each tool, they had a training stage to get familiar with the process and the tools specificities (e.g. commands in VR). Participants were provided with a step-by-step configuration guide with explanations to configure and test the light management service with the interaction technique T1. They only needed the microphone at this stage. Once they were trained with a tool, they were asked to configure and test the service with the interaction techniques T2 or T3 without detailed instructions. Both T2 and T3 required a depth camera to work properly. The overall experiment lasted up to 2 hours, with a mean of 1h16.

To prevent learning bias and bias caused by differences in instructions and difficulties, participants were dispatched into 4 groups presented in Table 1. These groups were named with the interaction technique and the configuration method they had to use at first. For example, the group that started with the OTF experiment while using the method T2 was "T2_OTF_first".

Table 1: The 4 groups of participants.

	Start with T2	Start with T3
Start with the OTF experiment	T2_OTF_first	T3_OTF_first
Start with VR	T2_VR_first	T3_VR_first

5.1.3 Participants

To preserve a similar diversity of experience in VR, gender, and age between groups, the 4 groups were similarly composed of 6 persons. Each group was composed of 5 males and 1 female. The mean (m) and standard deviation(sd) of the age per group were:

- m=37.7, sd=16.8 for "T2_OTF_first"
- m=35.8, sd=15.8 for "T2_VR_first"
- m=42.3, sd=12.3 for "T3_OTF_first"
- m=34.8, sd=15.7 for "T3_VR_first".

The groups that started in real had the same number of experts (i.e. participants with hours of experience in VR) and non-experts in VR (6 persons), while there were 7 experts for 5 non-experts for the other two groups. The experimenter and participants were UI designers, developers and researchers of the same company. Our institution doesn't have an ethical committee but we did our best to follow ethical principles: the participants were explained the experiment principles, they had to give their written consents and they could stop the experiment at anytime. Moreover, the

(a) (b) (c)

Figure 5: The two environments used for the experimentation: (a) the real one and (b) the virtual one. The green stars on (c) the top view of the environment represent the lightbulbs positions, and the red square represents the interaction space.

collected data was stored anonymously and the experiment didn't engage the participants in any hazardous situation.

5.1.4 Implementation and Hardware

Our MCEV tool is developed with Unity 2019.4 LTS [1], and the execution engine is implemented using ROS2 [2]. We used Google vocal recognition API to recognize the vocal commands. The MCEV tool ran on an Oculus Quest 2 headset connected to a laptop (RTX 2080, Intel Core I9-9900K, 32Go RAM) with the link mode.

The desktop tool was developed with the Python library PySimpleGUI [3] and was executed on a laptop (RTX 2070, Intel Core I7-10750H, 16Go RAM) for the OTF experiment. A Kinect (on a camera tripod) and a USB microphone were connected to this PC. The lightbulbs were Philips connected lightbulbs.

5.1.5 Collected Data

The completion times were recorded to compare the time performance in the OTF experiment and VR. Moreover, to compare the quality of the configurations created with both tools, we recorded the devices positioning each time the participants tested their configuration. We implemented a percentage scoring system to impose a minimal configuration quality on the devices positioning and coverage of the interaction space illustrated by the red square in Figure 5. A configuration was considered acceptable if the score for each device was high enough (above 75%). In practice, it was easily obtained as long as both the devices were not too far from the chairs and the camera had the chairs in its field of view. Thus, there was no specific optimal positioning that could be inferred from the score.

[1]https://unity3d.com/
[2]https://docs.ros.org/en/eloquent/index.html
[3]https://www.pysimplegui.org/en/latest/

At the end of each experiment, participants were asked to answer the NASA Task Load Index (TLX) questionnaire (Hart and Staveland, 1988), and could propose methods to accelerate the whole process. In addition, participants had to fill out the simulator sickness questionnaire (SSQ) (Kennedy et al., 1993) before and after the experiment in VR to verify if cybersickness had impacted the results of this experiment. The objective of these questionnaires was to evaluate and compare the overall cognitive costs of both methods with quantitative data. In addition, we wanted to compare the usability of both methodologies relatively to their device management process. Thus, we asked participants to rate the 3 7-Likert scale affirmations in table 6.

At the end, participants could comment on the overall experience, which gave us more insights into the experimentation results.

Id	Affirmations
FQ1	Placing and repositioning connected devices is easier ...
FQ2	Placing and repositioning connected devices is more permissive ...
FQ3	Identify connected devices is easier ...

Figure 6: Affirmations used to compare devices management in the OTF experiment and in VR, evaluated between -3 ("in real") and 3 ("in virtual reality").

5.1.6 Hypotheses

Our objective is to prove that our MCEV methodology could be a reliable alternative to OTF configuration and testing of MIBS. In particular, we think that our MCEV tool is more time efficient than a commonly used graphical tool such as our desktop tool, and we expect similar device positioning in both experiments. Moreover, we think that the advantages of simulation and immersion brought by VR reduce the arduousness of the configuration and testing process. We believe it is especially true when handling connected devices in multimodal and spatialized interactions. Thus our hypotheses are the followings:

H1) Configuring MIBS with the MCEV tool is faster than with the desktop tool, without degrading the result.

H2) The MCEV tool has a lesser cognitive workload than the desktop tool.

H3) The MCEV tool has a better usability than the desktop tool to identify, place or move the devices.

5.2 Results

5.2.1 Time Performance

To compare the time necessary to configure and test the light management service, we asked participants to perform the tasks in a timely manner. The participants could stop the experiments as soon as the score was above 75% for each device. The time taken to configure and test was recorded. The total time measurements are detailed in Figure 7. As we can see, participants needed more time to configure the service with the desktop tool than with the MCEV tool (a mean difference of 195s). Each participant performed in both real and VR, thus the measures are paired. As the results did not follow a normal distribution, we assess the significance of the result with a Wilcoxon test. The result (Z=-2.23, p=0.013) confirmed the initial hypothesis that it is faster to configure MIBS in VR with the MCEV tool than OTF with the desktop tool. In particular, we observed that the difference is significantly higher during the devices positioning step (mean difference of 150s, Z=-3.78, p¡0.01) and the testing step (mean difference of 108s, Z=-2.43, p=0.02) than in the other configuration steps.

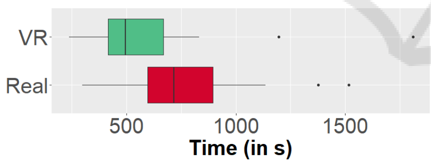


Figure 7: Total time to find an acceptable configuration.

5.2.2 Configuration Quality

The second part of hypothesis H1 is to ensure that the configurations performed with the MCEV tool are of the same quality as those performed with the desktop tool. More precisely, the quality criterion is based on the possible differences in the devices positions in VR and reality. For this, the final devices positions projected on the floor were saved, as shown in Figures 8 and 8. In these Figures, the final positions of each device are represented by transparent diamond points, while the mean positions are hexagons. We measured a mean distance (pair-wise) between the 2D positions in the OTF experiment and in VR for the microphone of 0.44m, and 1.10m for the camera. On average, it does not seem they are differences in the microphone positioning. For the depth camera, participants settled on more diverse final positions, especially in reality. Nevertheless, the depth camera average positions in the OTF experiment and in VR were roughly at the same place: in front of the three chairs. Therefore, there is no noticeable difference in configuration quality between both experiments.

5.2.3 Workload

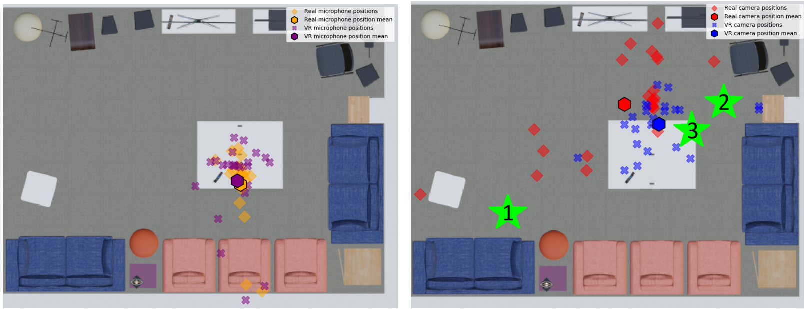
To evaluate the workload, we collected the results of the NASA-TLX questionnaires completed after each experiment. The results detailed in Figure 9 show that the workload seems slightly lower in VR than in reality. The results are paired similarly to the time performance measures, thus we performed a Wilcoxon test to evaluate the significance of this result. As a result, the global workload difference is not significant (Z=-1.34, p=0.09). For further analysis, we compared the results for each NASA-TLX factor, as detailed in Figure 9. No trend was observed on most parameters (p¿0.05) except for the performance criteria (Z=-2.51, p=0.006) which was higher in VR than in real.

5.2.4 SSQ

To assess if cyber-sickness has impacted the experiment in VR, we compared the SSQ results before and after this experiment. The measurements didn't follow a normal distribution, thus we used a Wilcoxon matched pair signed rank test to evaluate the significance of the questionnaire results. Even if the SSQ score significantly (Z=-3.45, p=$2.8*10^{-4}$) increased during the VR experiment (i.e. from a mean of 4.99 to 18.23), it remained low.

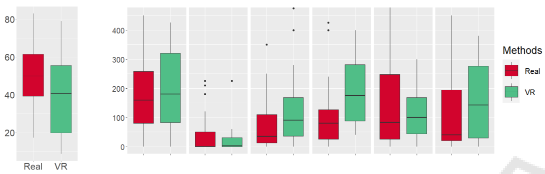
5.2.5 Usability

For the usability assessment of the MCEV tool compared to the desktop tool, we analyzed the results of the statements on the 7-Likert scale, detailed in Figure 10. For the 3 ratings, the result is in favor of the VR experiment. The rating distribution isn't normal, thus we validated the significance of this result with a Wilcoxon signed rank test under the null hypothesis that the ranks are lower or equal to 0. As the ratings are significantly higher than 0 (FQ1: Z=-3.43, p=$3.0*10^{-4}$, FQ2: Z=-3.62, p=$1.5*10^{-4}$; FQ3: Z=-3.31, p=$4.6*10^{-4}$), it confirms that the MCEV tool was considered more usable than the desktop tool when handling connected devices (H3).



(a) (b)

Figure 8: (a) The microphone and (b) the depth camera final positions for all configurations, and the mean positions. The green numbered stars in figure (b) are respectively the initial positions of the camera, microphone and laptop in the OTF experiment.



(a) (b)

Figure 9: (a) Global and (b) detailed workload ratings.

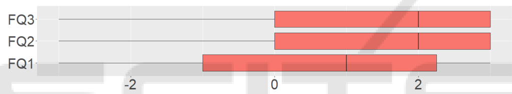


Figure 10: Rating for the table 6 statements, between -3 and 3.

5.3 Participants Feedback

First, most participants reported difficulties placing the camera in the OTF experiment, and lost time doing that. We observed that most participants had to go back and forth several times between the camera to place it, and the laptop hosting the desktop tool for the visual feedback. Even further, they didn't move the laptop to reduce the problem, even though they were expressly allowed to do that in the instructions. There were even participants who didn't use the visual feedback of the camera at first, as they reported they were confident in their camera placements. In comparison, we observed that most participants didn't have issues placing the camera in the MCEV tool, and were relatively fast at finding a seemingly acceptable position. Second, some participants reported their concerns about the realism of the device positioning in VR. For example, it was possible to place the devices (e.g. microphone) under or "in" the furniture in VR. Some participants tried such placements during the experience, but they settled for more realistic locations in the end.

5.4 Discussion

5.4.1 MCEV Tool Performance

Our hypothesis H1 is validated. Indeed, participants were faster with our MCEV tool (mostly during the devices positioning and testing steps), and the devices were roughly positioned in the same areas. Our observations indicate that having a device feedback displayed closely to its device is time-saving during the devices positioning step in VR (as in Figures 1 and 3) compared to OTF where the participants had to regularly move the laptop (or walk back and forth) to check the sensors feedback while manipulated them. Similarly, the fact that device locations are directly accessible in VR could help to avoid errors and approximations, thus it could also have a positive impact on the time performance. The performance difference in more complex use cases (larger environments, more devices, more elaborate services), such as a service to guide newcomers in an ubiquitous computing office needs further exploring. We believe the time performance would be even better in VR for these demanding scenarios, as it would require more iterations of devices positioning and testing.

However, some participants tried unrealistic positions in VR, and had concerns about the process of replicating the configurations made in VR to the real environment. Indeed, the realism of the devices positioning was not measured or constrained, and our experiment relied on the participants to define what was acceptable and what was not. Moreover, the quality of the configurations was only calculated from the devices locations on 2D dimensions. We set this limitation to compare the devices positioning in real and VR with similar information. However, environmental factors such as 3D obstacles or the soundscape could impact the configurations quality. Thus, the realism of the VR environments and the quality of support provided by the MCEV tool could impact the time needed to install MIBS, and it could lead to more in-depth experiments. Nevertheless, the MCEV tool could be improved with a method to automatically generate warnings and recommendations of devices positioning from the devices and environment information.

5.4.2 MCEV Tool Cognitive Load

Contrary to our hypothesis H2, our results suggest that the desktop and MCEV tools have no verified differences in cognitive load, except for the performance criteria. This absence of difference in usability could be explained by the sobriety of our experiment. Indeed, we considered a diversity of participant profiles, we limited our experiment to one simple scenario in one room, and we didn't experiment on the collaborative features. As stated before, we agree with some of the participants' feedback that suggest the advantage of VR could become more significant with situations on a larger scale and complexity. The performance difference in the NASA-TLX could be explained by the difficulties most users had to understand that the virtual and the real camera shared the same *aura*.

5.4.3 MCEV Device Management Usability

Our hypothesis H3 is validated, which means that identifying and moving devices is considered easier with the MCEV tool. The difficulties to handle devices with non-trivial aura such as the depth camera in our experiment seems to be the main reason to the usability (and time) differences between both experiments. This suggests that the MCEV methodology is beneficial for MIBS that heavily rely on unidirectional sensors. The relevance of device positioning in VR could be further evaluated in more complex scenarios. Indeed, the simulated and real devices were roughly placed at the same position in average. However, our scenario was limited to a relatively simple environment without disturbances or considerable difficulties.

6 CONCLUSION AND FUTURE WORK

In this article, we have proposed a methodology and software tool based on VR to facilitate the configuration and evaluation of MIBS. Thanks to 3D interactions, it aims to facilitate the selection and positioning of devices and their association with newly configured multimodal interaction techniques and services. The created MIBS can then be evaluated in immersion without needing the real environment. Finally, the evaluated configurations can be shared with our proposed collaborative features to improve the MIBS or facilitate the installation in the real environment. We conducted a user experiment to compare the efficiency and usability of our tool to the ones of a desktop tool we developed to adapt our methodology process to OTF experiments. The results show that the configuration and installation process is more efficient with our VR tool, and that it has at least the same usability as the desktop tool. Thus, we believe that our proposed methodology and tool based on VR propose a valid alternative to OTF experiments and could promote the democratization of MIBS.

In future work, the proposed collaborative method needs to be evaluated by MIBS producers and administrators to validate the supposed advantages during the integration and installation process. Thus, we plan to evaluate the usability and completeness of our tool collaborative features with ergonomists. We also plan to create complex configurations with ergonomists and ask MIBS administrators to install and evaluate them in the real environment.

We are also working on new device management features such as automatic recommendation areas for devices and warnings to prevent errors. We are also implementing an interactive World-in-Miniature (Stoakley et al., 1995) to have a more complete view of the environment, and easily move in large environments. Finally, we are working on an AR solution to configure and evaluate MIBS in real environments when they are available. The objective is to facilitate the transition from the virtual to the real environment by configuring and testing with real devices alongside the virtual ones.

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