MW4HBI: Mobile and Wearable Human-Building Interactions with a Multi-Platform User Interface

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***Abstract*—In this paper we introduce Mobile and Wearable Human-Building Interactions with a Multi-Platform User Interface (MW4HBI). We start with laying out the guidelines to design responsive user interfaces for mobile and wearable devices. Then, we provide technical specifications for deploying a multi-platform application that manages entertainment and household appliances in smart buildings via a variety of input devices. Finally, we present the results of a small-scale end-user study on the preferences for ambient parameters inside smart buildings.**

Keywords—smart buildings, ubiquitous computing, mobile computing, wearable computing, responsive design

I. INTRODUCTION

Interest in smart buildings dates back many years, starting in 1981, when United Technology Building Systems Corporation coined the term *intelligent building* [1]. Since then, the concept has been constantly developed, and the notion of *smart building* has emerged. The distinction between the two ideas is somewhat blurry [2], but the terms are more or less associated with self-sustainability and energy management. In the light of rising climate change concerns, global consumer behavior has changed significantly, i.e. they tend to reuse more, minimize food waste, and switch to sources of reusable energy [3]–[5]. These trends have resulted in an abundance of research studies that concentrate on optimizing the potential of renewable energy sources and judicious resource utilization. Many of them propose artificial intelligence-based applications aimed at lowering energy use and achieving energy independence [6]–[9], while upholding user preferences and comfort levels, as comfort is a core value in smart building research [10].

Let us use a straightforward scenario to illustrate an example of human-building interaction. *John comes home tired after a long day of work. He wants to enjoy himself, so he walks to the dashboard controlling the appliances in his home, selects a white light tone appropriate for reading, and puts on some nature sounds to help him relax. He reads for a couple of hours, then he wants to watch his favorite TV show. Therefore, without leaving his comfortable couch, he takes out his smartphone and dims the lights, selects a violet color for ambient lighting, turns off the ambient sound, and turns on the ventilation system. After watching his show, he goes to bed. In bed, he remembers he forgot to turn off the lights and the ventilation. He opens the application on the smartwatch, that he always wears, and does exactly that.*

There are numerous software solutions available on the market that specifically target this scenario, such as Philips' Hue and Govee's Home smartphone applications. However, they are not usually available on many platforms, have a very inflexible user interface and they are not compatible with a wide range of devices, i.e. most of them are only accessible on smartphones and work with proprietary appliances. There are other web platforms, such as Home Assistant and IFTTT that allow users to interface with smart devices from a large number of manufacturers, but they are not always easy to use for the average consumer.

In this article, we take a different approach to developing software applications for controlling smart buildings. The usage of mobile and wearable devices is following a rising trend, and we think this should be taken into consideration from the outset of the design process. As a result, we propose a multi-platform, adaptive user interface (UI) dedicated to controlling devices in a smart building, which changes depending on the screen size of the device on which it is rendered; see Fig. 1 to see how the above scenario translates to application changes. This UI adjusts depending on the screen size and the internal state of the system, highlighting the widget which is most likely to be of interest for the user. Lastly, we use this application in a user preference elicitation study regarding optimal values for ambient parameters such as light, sound and airflow.

II. RELATED WORK

There exists a very extensive body of work on the topic of human-building interaction. In this section, we discuss a number of such applications for managing home appliances, and highlight the need for incorporating wearable devices in the research.

Jazizadeh and Becerik-Gerber [11] introduce a software application dedicated to smartphones, that gives users control over ambient lighting and the heating, ventilation and air conditioning (HVAC) system. The users have the freedom to change the intensity of the ambient light, select the desired intensity of the air currents and achieve personal thermal comfort by turning the HVAC system on and off. This paper also underlines the need for the personalized ambient settings in order to increase the comfort of inhabitants of a smart building.

Lim et al. [12] report positive results from a research conducted in a pediatric hospital setting. The study aimed to assess the ability of interactive technologies to capture and redirect patients' and visitors' attention to relaxing activities. The hospital reception room was equipped with an interactive floor that simulated a pond using a video projector. Then, they used user presence and movement as an interaction technique with the projection. For instance, virtual fish avoided areas where users were present. The study's findings demonstrate

This work is supported by the NetZeRoCities Competence Center, funded by European Union – NextGenerationEU and Romanian Government, under the National Recovery and Resilience Plan for Romania, contract no.760007/30.12.2022 with the Romanian Ministry of Research, Innovation and Digitalisation through the specific research project P3-Smart and sustainable buildings.

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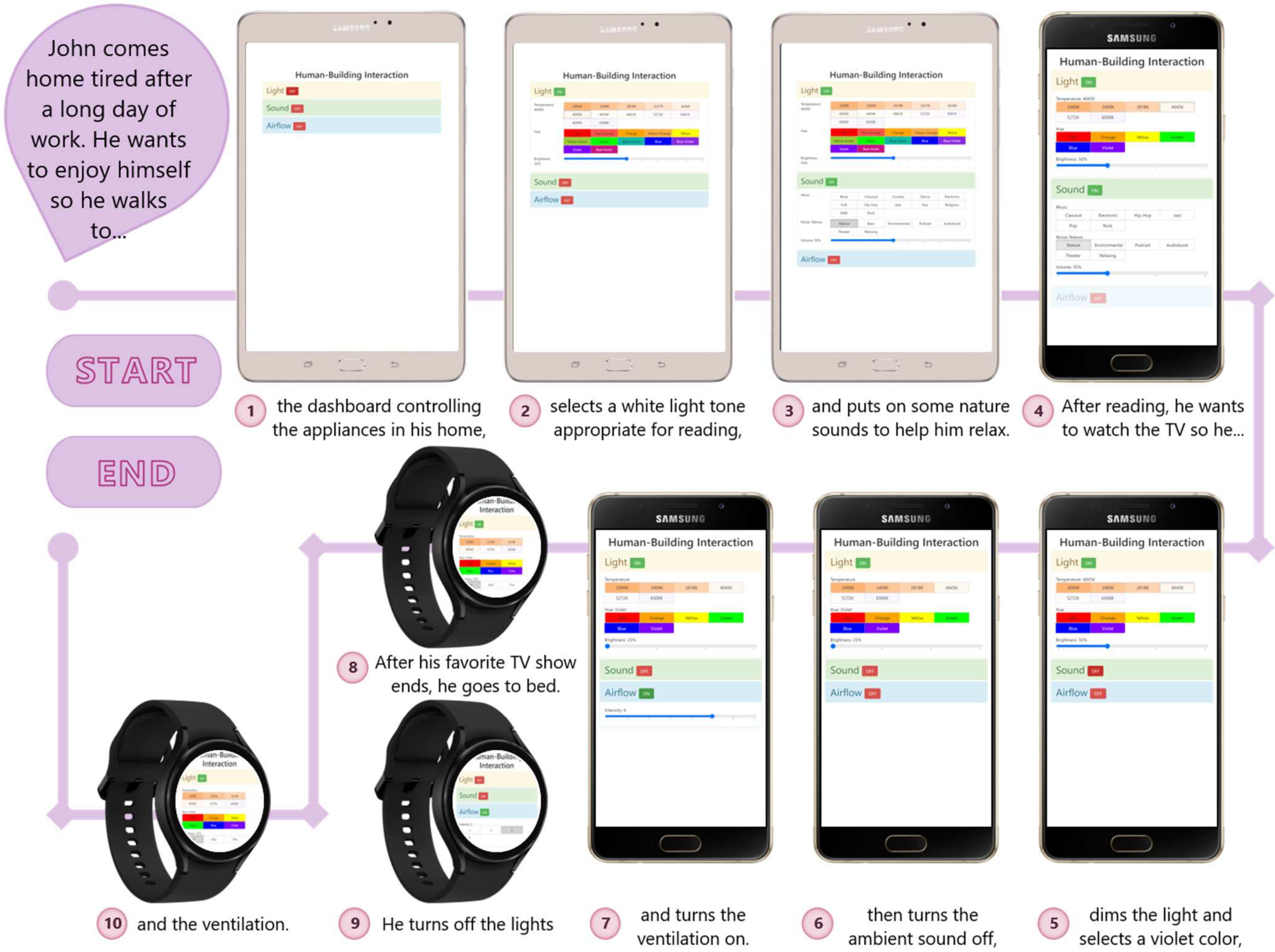

Fig. 1. Example workflow using three input devices: a tablet, a smartphone, and a smartwatch; see Section I for details

that this system effectively piques curiosity, particularly among children, who tried out various methods of interacting with the system, such as using different body parts.

Hilo-wear [13] is a smartphone application that monitors the level of carbon dioxide in an office and notifies the users to take action in order to prevent poor air quality in the room. It analyzes ambient data gathered by *Hilo-box*, an environmental monitoring device that collects information about humidity, air temperature, pressure, particulate matters, and other environmental parameters. Moreover, the system is able to formulate short term predictions (20 minutes) about the evolution of the air quality.

Other applications focus on natural interaction modalities such as gesture or voice input. For example, *Tap4Light* [14] uses a hand-augmentation device to detect tap gestures performed on any surface, and translates them to changes of ambient light parameters. Andrei et al. [15] examined the possibility to interact with devices in smart building using hand-chair gestures, which are gestures performed on and around chairs. Șiean et al. [16] explored multiple locations in a smart environment where radar sensing devices could be incorporated. In this way, users can perform gestures close to the devices they want to interact with, and see the action in real time. *WearSkill* [17] is a web-based application that enables users to define personalized touch and gesture input, which remains consistent across multiple wearable devices. One may use *WearSkill* to implement custom gestures for the interaction with a smart TV or with ambient lighting devices [18] inside smart buildings. *Euphoria* [19] describes three interaction modalities with digital content for smart environments and in-vehicle scenarios. These scenarios involve storing digital content in the pockets of the users' clothes and play it on an ambient display, accessing spatially-indexed media [20] with their smartphones, and receiving notifications on wearable devices while driving a vehicle.

When it comes to responsive design, there are many different systems addressing adaptive interfaces that have been documented in the scientific literature. These applications span a wide range of usage scenarios, from assisting users with everyday tasks to producing customized content for virtual reality (VR) navigation and highlighting accessibility features for people with motor or visual impairments. For instance, Hu et al. [21] address the problem of generating adaptive TV GUIs from smartphones in an efficient and automated manner. Their approach involves the analysis of the smarpthone GUI's metadata to identify atomic interface components, their hierarchy and the way they interact with each other. Then, they group interface components in categories based on their relationship, and match them onto TV UI templates. After optimizing the resulting templates, they are used as a base to generate code in a cross-platform TV GUI Domain Specific Language (DSL). This code can further be used to render the corresponding user interface on the TV. *Mo-Bi* [22] is a context-aware interface

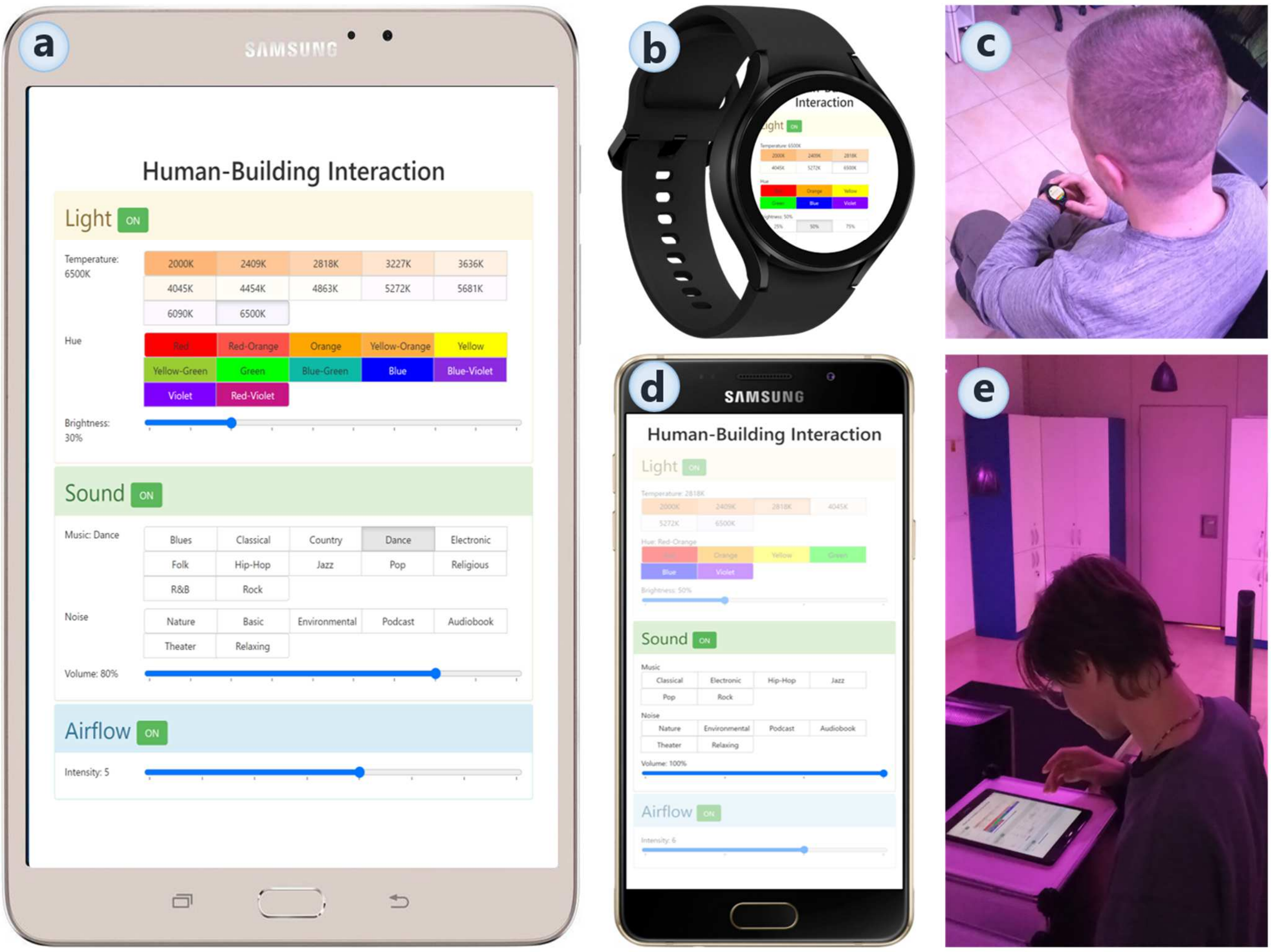

Fig. 2. (a), (b), (d) - MW4HBI exhibited on screens of different sizes. (c), (e) - Participants using MW4HBI during the user study for evaluating user preferences for ambient parameters inside smart buildings.

that monitors the user's hand position and makes everyday tasks like drawing or taking pictures easier by incorporating new features into system applications. Reference [23] proposes two implementations of adaptive GUIs using fuzzy constraints which represent the mapping between the widgets and their desirability as their satisfaction degrees. The news application detailed in [24] splits its users into three groups based on their activity patterns — *Trackers*, *Reviewers* and *Dippers* — then, it modifies the layout to show the appropriate content for each group. The system proposed by Hu et al. [25] uses a smartphone's built-in Inertial Measurement Unit (IMU) to detect whether the user is moving and adjust the size of UI elements. The application described in [26] assists individuals in achieving their weight loss goals more quickly by monitoring their caloric intake and making recommendations that are in line with their objectives, and that in [27] proposes an adaptive VR interface that lets users personalize how they access information in a virtual setting. Last but not least, *FrameKit* [28] is a tool dedicated to aiding designers in creating adaptive user interfaces (AUIs) with the goal of improving the overall user experience of their application. It allows for the easy construction of widgets, which can be automatically mixed together in order to generate new variations of one interface based on user-defined keyframes.

Nevertheless, despite the broad range of applications, we have not been able to find articles that discuss the use case of controlling entertainment devices and home appliances. These factors contributed to the creation of Mobile and Wearable Human-Building Interactions with a Multi-Platform User Interface (MW4HBI), which, to the best of our knowledge, is the first multi-platform application, having an adaptive user interface, designed specifically to control devices in smart buildings.

III. Mobile and Wearable Human-Building Interactions with a Multi-Platform User Interface

MW4HBI is a software application which uses state-of-the-art consumer electronics and industry-proven software components to present mobile and personalized interaction modalities in smart buildings. This section contains an overview of the design requirements we adhered to when developing the application, along with technical implementation details about the hardware and software we used.

A. Design requirements

When developing the system, we followed Nielsen's usability heuristics [29] and the design framework for adaptive pointing proposed by Martin-Hammond [30], while also keeping in mind that *different screen sizes derive different benefits from adaptive interfaces* [31]. In the end, we settled upon the following design requirements:

- *High portability.* As of right now, mobile devices account for the majority of all Internet traffic (with smartphones accounting for 58.54% and tablets for 2.05%) [32]. At the same time, 96.50% of smartphone users access the internet frequently [33]. In this context, it makes sense to take a mobile-first approach when designing software applications. Web applications are the ideal option since they completely meet this requirement without requiring extra work from developers. Instead of having to oversee several projects for various platforms, they let developers maintain a single, high-quality codebase.
- *Adaptive UI.* Users have different needs at different times and in different contexts. However, they behave in a fairly uniform manner during every usage session. Because of this, a fully adaptive, unpredictable user interface would be challenging to use, whereas a static user interface might not be advantageous in a mobile context. We therefore made the decision to raise the adaptivity level of the UI as the device's screen size drops. Although some research indicates that adaptive interfaces with duplicate UI elements are more usable [34], we reason that this will actually make them less usable in the context of smaller screens. Thus, rather than duplicating elements of interest, we chose to increase their saliency [35] by slowly fading in irrelevant UI components.
- *Simplicity in use.* As software applications become more complex, the user interface can quickly become cluttered. This and the fact that some tasks are challenging to complete on smaller screens [31] prompted us to eliminate some elements of the user interface designed for smaller screens. This constitutes a middle ground between the ideas of *keeping the users informed* and *putting them in control* [30]. We argue that by restricting the options accessible on smaller screens, we actually improve the usability of the application.

B. *Hardware*

To illustrate interactions within smart buildings, MW4HBI makes use of commercially available hardware in order to allow users to adjust the ambient sound, light, and airflow. For that, it utilizes six Power Dynamics PDS40 speakers (working under four power tappings: 3.75W, 7.5W, 15W, 30W; having a frequency response in the 70Hz-20kHz band), six Philips Hue A60 light bulbs (displaying over 16 million colors, or white light with a temperature in the 2000-6500K interval), and a Govee Smart Tower Fan H7101 (having three functioning modes: sleep, nature and normal; allowing control over the fan power in eight levels). Lights and speakers are managed by a Philips Hue Bridge, and an Audio Line MPA 120B mixer, respectively. Tablets, phones, and smartwatches, display the GUI that allows users to personalize the scene. For this application, we used a Samsung Galaxy Tab A 7.0 tablet (backed by Quad-core 1.3 GHz Cortex-A53 and Quad-core 1.5 GHz Cortex-A7 CPUs and 1.5GB of memory), a Samsung Galaxy A3 smartphone (having a Quad-core 1.2 GHz Cortex-A53 CPU and 1GB of memory), and a Samsung Galaxy Watch 4 smart watch (working with a Dual-core 1.18 GHz Cortex-A55 CPU and 1.5GB memory).

C. *Software*

The software architecture follows the client-server model. The client application is implemented using HyperText Markup Language (HTML), Cascading Style Sheets (CSS), and JavaScript. Bootstrap, a popular front-end framework, was used in order to add responsive features, i.e. to resize the layout depending on screen size. The client's purpose is to present the UI to the users and to make asynchronous requests to the server on user actions; it achieves that by using JavaScript's Fetch API.

The server comprises a Flask application, written in the Python programming language, responding to client requests. It comprises three modules responsible for controlling ambient light, sound and airflow. The ambient light and airflow modules make HyperText Transfer Protocol (HTTP) requests to the Hue and Govee APIs, respectively, in order to adjust the lights and airflow. The ambient sound module makes use of the soundfile and sounddevice open-source libraries in order to play audio files. Sound files are stored on the computer that hosts the server, which is connected to the Audio Line MPA 120B mixer. When the user selects the type of ambient sound they want to hear, the client makes an asynchronous request to the server, which loads the corresponding sound file, and sends it over the audio mixer, via a Bluetooth connection, to be played.

D. *User Interface*

The user interface is responsible for showing the users relevant system status and giving them the opportunity to make changes according to their wishes. MW4HBI adjusts depending on the device screen size. Consequently, it allows for finer control of light, sound and airflow parameters at larger screen sizes and becomes increasingly focused on providing coarser control of the same parameters as screen size decreases.

At full size, MW4HBI allows the user to choose between 12 white light temperatures (in the interval 2000K - 6500K) and 12 colors (i.e. primary, secondary, and tertiary colors), as well as adjust light intensity in 10 levels (10% - 100%). Likewise, users can select 12 types of music (blues, classical, country, dance, electronic, folk, hip-hop, jazz, pop, religious, rock, and R&B) and 7 types of ambient sounds (nature, basic, environmental, podcast, audio book, radio theater, and relaxing) and control the volume within a range of 10 levels. The airflow settings allow users to control the fan speed in 8 levels (limited by the smart tower fan). In the case of smartphones, the parameter range is more limited. Instead of 12 light temperatures and colors, the user only has 6 options to choose from (i.e. primary and secondary colors) and the brightness can be varied in 4 levels. The same applies to sound and airflow control. The UI also highlights settings that may be more relevant to the current user — irrelevant layout components fade in slowly [35]; see Fig. 2.d where *Light* and *Airflow* settings have a higher transparency than the *Sound* settings. However, on wearable devices, in addition to the changes that apply to the smartphone interface, all sliders are replaced with buttons to improve accuracy. Because MW4HBI needs to be consistent across devices, the current system status is displayed in each session. This means that a change made by one user also affects the devices of other users. Fig. 2.a, 2.b, 2.d show how MW4HBI looks on devices with different form factors.

E. *Preliminary evaluation*

The validity of our approach was assessed through both automated and manual testing. During the application development, we followed a Test Driven Development (TDD) approach, which included periodic running of unit tests and regression tests. Manual testing was conducted on three input devices: a tablet, a smartphone, and a smartwatch, whose characteristics are detailed in subsection III.B.

Furthermore, the application was used in an end-user study investigating preferences for ambient lighting, sound and airflow in smart buildings. The study comprised five participants (3 self-reported females and 2 self-reported males) aged between 19 and 21 (M=20.4, SD=0.9). All participants mentioned frequent use of smartphones and smartwatches, and occasional use of tablets. They were given a time slot of 15 minutes to test the application on the tablet (see Fig. 2.e), smartphone, and the smartwatch (see Fig. 2.c), then they expressed their preferences for ambient parameters by answering a questionnaire. Before commencing the study, participants were asked to sign a consent form, then filled out a demographic questionnaire.

Table I depicts user preferences in terms of white light, colored light, ambient noise, ambient music, and airflow intensity for activities such as eating, watching television and studying. For white light we notice a proclivity for cool tones (around 5000K), and, for colored light, there is a clear inclination for shades of violet. Soothing noises such as nature and basic sounds (i.e., crickets chirping and people whispering, respectively) were the most preferred ambient noises. In terms of music, only one participant chose hip-hop music, while the others chose electronic and blues, each with two votes. When it comes to the intensity of the ambient parameters, there is a tendency to choose high values (over 50% for light brightness and sound volume, and over 6 out of 8 for the intensity of the air currents), which could result in a higher than usual energy consumption.

A post-study discussion with the participants revealed the users' desire to use such applications for controlling appliances in their homes, all of them stating that it would make the interaction with smart devices easier due to its convenience and effectiveness. Two participants stated that even though they own virtual assistant systems, they would prefer to use MW4HBI instead, because it is straightforward and easy to use.

IV. Conclusions and Future Work

In this paper, we presented Mobile and Wearable Human-Building Interactions with a Multi-Platform User Interface, which broadens the scope of adaptive graphical user interface research by including wearables like smartbands and smartwatches. We presented the technical specifications for putting into practice a software application that will allow users to control entertainment and household appliances in smart buildings using a wide range of input devices. We also discussed the design requirements for adaptive wearable interfaces. We presented user preferences for ambient parameters resulting from a small-scale user study, and reported positive reviews demonstrating the viability of our application as a means of managing smart entertainment systems and appliances within smart buildings.

In contrast to other approaches, such as hand-chair gestures [15] and radar gestures [16], which make use of hardware devices embedded into the environment, MW4HBI utilizes the users' personal devices as a support for the interaction with the smart building. Therefore, it provides a consistent user experience across multiple input devices, while improving efficiency on small screen sizes by the means of adaptive design techniques. Future work to further develop this concept includes expanding the range of devices used, both input and output, as well as validating the concept in more a structured and broader user study. We are currently working on expanding the list of input devices to include Vuzix Blade smart glasses. Next steps include further customization of the user interface using AI models.

TABLE I. User Preferences for Ambient Lighting, Sound and Airflow Inside Smart Buildings

Participant	White light		Colored light		Ambient noise		Ambient music		Airflow
	Temperature	Brightness	Hue	Brightness	Type	Volume	Genre	Volume	Intensity
1	4863K	50%	Red-Violet	100%	Basic	100%	Hip-Hop	100%	7
2	6090K	90%	Blue-Violet	90%	Nature	50%	Electronic	80%	2
3	4863K	80%	Blue-Violet	60%	Nature	30%	Blues	90%	1
4	4454K	80%	Red-Violet	60%	Podcast	90%	Electronic	70%	7
5	3636K	80%	Orange	80%	Basic	30%	Blues	50%	6

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