Exploring an Architectural Framework for Human-Building Interaction via a Semi-Immersive Cross-Reality Methodology

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Figure 1: From left to right: a photo of the home of participant P4+P5; its virtual simulation; its simulation with a responsive wall in condition MF, and participant P3 experiencing the semi-immersive cross-reality simulation of her home.

ABSTRACT

The vision of responsive architecture predicts that human experience can be evoked through the dynamic orchestration of space-defining elements. Whereas recent studies have robotically actuated furniture for functional goals, little is known how this capability can be deployed meaningfully on an architectural scale. We thus evaluated the spatial impact of a responsive wall on the inhabitants of ordinary apartments. To maintain safety during the COVID-19 pandemic, we developed a novel remote, semi-immersive cross-reality simulation evaluation methodology. Based on the orchestration of three space-defining operations, we define a theoretical framework that suggests how the position of a responsive wall can be determined through five distinct architectural qualities. This framework thus proposes how human-building interaction (HBI) could complement its functional goals with augmenting the well-being of occupants in the physical as well as the virtual realm.

CCS CONCEPTS

• **Human-centered computing** → *Empirical studies in HCI*.

KEYWORDS

robotic furniture, interactive architecture, responsive architecture, human-building interaction, cross-reality simulation

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1 INTRODUCTION

Well-experienced architects believe that the purposeful orchestration of architectural qualities such as material, shape, acoustics or light, is able to evoke the human experience of space insofar that it might even influence the health and well-being, thoughts, emotional states and behaviors of its occupants [29, 46]. Inspired by visionary architectural thinkers in the 1960s [19, 45, 66], efforts in the fields of *interactive, responsive, adaptive, flexible, smart, reactive, kinetic* or *intelligent* architecture believe that this orchestration could even pro-actively [64] change in real-time and all the time [43], to adapt to the needs of occupants [49] in ways that are perhaps more effective and compelling than that of 'static' architecture [36]. Recent studies demonstrate the feasibility of modern robotic technologies to physically alter architecture in at least four of its six prototypical layers [15], as it is now possible to move sofas, chairs [1, 52] and room dividers, [54], or change the shape of a whole structure [25, 44]. As most of these advances have been primarily motivated to reach functional goals, it is however not yet known whether and how such dynamic spatial adaptations can influence the experience of space as envisioned by responsive architecture.

We thus propose that responsive architecture can only compete with its static counterpart when its dynamic adaptations are functional, i.e. affording or restricting specific activities to take place; but also architectural, i.e. generating atmospheres that are compelling. This study therefore explores the impact of a life-sized wall

Figure 2: A comparison between the participant homes and their respective abstracted virtual simulation. From left to right: the homes of P3, P4+P5 and P6.

as a responsive element, since its space-enveloping scale is perhaps the most fundamental and elementary aspect that determines the architectural experience [17]. Not only can a wall create multiple physical spaces where there was originally one, it can also affect the overall atmosphere by providing or withdrawing architectural affordances like visibility, circulation or lighting; or sensory cues like acoustics, temperature or ventilation. To overcome the worldwide quarantine restrictions from the COVID-19 pandemic, we observed the impact of this responsive wall by videoconferencing with participants in their own homes, as they narrated and walked-through a self-directed 3D virtual simulation of their domestic environments. This study thus contributes: 1) a new evaluation methodology to capture spatial experience in private and sensitive settings; 2) the self-reported evidence of how common people potentially experience a responsive wall in their own everyday homes; and 3) a theoretical framework that relates architectural reasoning to the responsive behavior of a space-defining element.

The field of evidence-based design [55] provided the first empirical evidence that the design of our built environment affects the health and well-being of humans [46], demonstrating that 'good' architecture has measurable implications on our quality of life [53]. Making spaces adapt or behave in ways that are architecturally motivated therefore does not only have the potential to make indoor spaces more flexible and functional, yet also more pleasurable and healthy. While this research focuses on the architectural potential of responsiveness in the physical realm, we believe our findings can be equally useful in cross-reality and virtual reality environments.

2 LITERATURE

2.1 The Experience of Space

Architectural phenomenology has since long focused on the embodied, first-person experience of space [37] by arguing that space is politically produced through how it is perceived (e.g. activities), conceived (e.g. plans) and lived (e.g. symbols and images) [28], and by proposing that architectural design should be based on human experience rather than on abstract rationales that may not affect its users [7]. The notion that the holistic orchestration of architectural qualities such as materials, colors, light and forms [26] impact the thoughts, emotions and behaviors of occupants [18] has motivated recent studies that discovered how the carefully-designed atmosphere in a cancer-care building helps shape how daily care is staged, practised and experienced [33], or how the atmosphere of a carefully orchestrated museum space opens up serendipitous experiences for its visitors [31]. Neurophysiological experiments rather focus on measuring the impact of one particular architectural feature on human mind and body [13], revealing how architectural curvatures provoke more pleasurable and aroused feelings [10], rooms with wood help relieve stress and tension [65], and open-plan rooms with higher ceilings are considered more aesthetically pleasing [59]. The discipline of Evidence-Based Design (EBD) measure whether and how such spatial features are beneficial to the health and well-being of occupants [55] by focusing on how effective ventilation, acoustics, natural distractions, daylight, appropriate lighting, ergonomic design, acuity-adaptable rooms or improved floor layouts affect patient health and staff satisfaction [56]; how physical layouts, affordances and configurations influence the way in which work organisations communicate, interact, and perform [50]; and how open views and natural daylight benefit physiological and psychological health [60].

The human experience of space has also been studied in the virtual realm by measuring how users engage with highly realistic digital simulations [39]. Studies that compared the experience of physical versus virtually simulated architecture revealed strong correlations in terms of how people behave in space [21], evaluate the atmosphere [27], perceive proportions [62] and spatial measures [57], feel immersed [51], or emotionally respond to light, color and texture [42]. Based on these strong correlations, virtual reality (VR) has been applied as a alternative medium to explore architectural experience, such as to discover the impact of supplementary home spaces on emotion [20], furniture arrangement on the cognition of spaciousness [35], and architectural interior forms on brain dynamics [10, 13].

2.2 Human-Building Interaction

The field of Human-Building Interaction (HBI) [2, 64] tends to capture the situated experience of space by actively engaging occupants through workshops, building walks or speculative futuring [38], or by covertly observing or proxy-interviewing them [30]. By developing new technological tools that sense occupancy rates and navigational patterns [61], HBI has modeled complex space use behaviors in order to ascertain that the visual situation around a work space determines whether or not it is regularly used [4], or that the facilitation of human control over dynamic building elements causes occupants to be more conscious of their environmental conditions [14]. Other HBI studies revealed how humans experience robotically-actuated objects in space, by demonstrating how the behavior of a robotic sofa can be designed through different levels of improvisation that focus on the aesthetics of interaction [52] or how a robotic chair can invite passers-by to join a chess tournament by way of its dynamic movements [1]. More artistically-inspired HBI research explored the aesthetic experience of occupants with and within responsive architectural elements, by measuring the impact of a moving beam on nearby museum visitors [12], discussing the mutually intimate and reciprocal responses of the human body versus the encompassing space by observing how a dancer interacts with a room made from dynamically moving fabrics [58], or revealing how the physiological behavior of occupants tends to

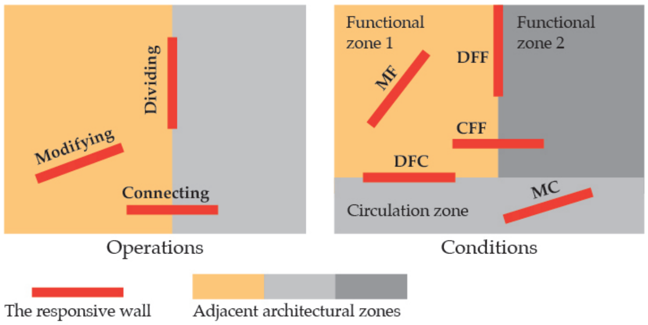

Figure 3: The three spatial operations of a responsive wall, which can either divide, modify or connect one or more adjacent functional zones and/or one adjacent circulation zone.

synchronise with the dynamic movements of a tent-like structure [24]. Other HBI research investigated how responsive architectural elements can be actuated more in the background of human attention, such as by projecting a graphical pattern onto curtains that gradually adapt to the preferences of the occupants [9], by altering the shape of a large wall-canopy in a work context [23], or by exploring how transparency-changing domestic windows could be used as an ambient information display [8]. Despite these rich scientific explorations, to the best of our knowledge HBI research has not yet considered the architectural phenomenological sensitivity to design its responsive interactions around the embodied, first-person experience of space.

3 METHODOLOGY

As it is known that realistic VR simulated architecture can provide the experience of space corresponding to its physical counterpart [21, 51], our original evaluation methodology meant to compare how different participants experienced a fully immersive simulation of one identical architectural space. Because national quarantine restrictions due to the COVID-19 pandemic withheld people to leave their homes, we realised that our participants could only experience our 3D simulation from their own homes. We thus found it logical to simulate the actual homes of the participants themselves instead, by hypothesising that the loss of generalisability when comparing the experiences of a prototypical - but also foreign and artificial - space could be compensated by the familiarity of one's own home, as a home-bound participant would be able to serendipitously notice situated cues from the physical realm. The study occurred with the permission from the Ethics Committee of our university, which included additional attention to follow COVID-19 guidelines.

3.1 Architectural Simulation

All participants were voluntarily recruited via social media. Because sharing information about one's home involved a certain level of trust and accountability, most participants originated from a Facebook group of the residence where the primary author lived. Each participant was requested to submit a floor plan sketch, a set of rough physical measurements and a small collection of images of their homes; and briefly describe the prototypical locations of daily habits. All this data was used to model each home into a virtual simulation using Unreal Engine (UE4). Modeling took approximately 1 day per home, plus an additional day to integrate all experimental conditions in the unique architectural context. Participants were able to navigate in the virtual simulation via default keyboard combinations (WASD and/or arrow keys) and mouse movements of UE4 on a laptop, or via the integrated UE4 touch interface on a tablet computer. Inside the virtual simulation, a custom user interface presented a drop-down list of predefined wall locations and a checkbox to determine if the wall should move to the target location or "teleport" instantaneously, such as to quickly compare two spatial conditions with each other. Each virtual simulation was stored on the computer of the researcher, which participants remotely accessed via the Google Chrome Remote Desktop extension. While this approach allowed participants to use their own personal device, it avoided us to remotely or physically access it in any way. Instead, all audiovisual communications were captured via Skype videoconferencing software, while the virtual simulation was recorded by dedicated screen recording software on the researcher's computer. Each virtual movement was also logged by recording the timestamp, location and viewing direction of the participant and the wall.

3.2 Architectural Fidelity

As shown in Figure 2, each home was simulated as an abstracted, grey-scaled environment since a simplified virtual model does not necessarily impact the overall architectural experience [21] insofar that the emotional qualities of architectural space can be conveyed by the minimal simulation of lights and textures [42]. We also expected that this stylistic abstraction would encourage participants to focus on the overall spatial experience rather than on the level of realism, as they should be well-aware of the lived-in details of their own homes. The responsive wall measured 200cm x 200cm x 40cm to ensure that it could project a significant 'weight' in the space (depth), physically separate different zones from one another (width), and still move through a typical door opening (height). Its materiality resembled white plaster, to avoid that the wall would stand out as an individual object and to make subtle environmental aspects like lights, shadows or views more pronounceable.

3.3 Experimental Setup

Each floor plan was analyzed using a standard architectural zoning method that distinguishes spaces or zones within spaces by their functionality [16]: *functional* zones are dedicated to host a core activity such as relaxing, working or cooking - among many others; while *circulation* zones host no dedicated activities but allow people to extend, or move between, one or more functional zones. As shown in Figure 3, we assume that a responsive wall is able to impact two zones in three distinct ways, i.e. by: 1) *modifying* the zone it is located within; 2) *dividing* two adjacent zones from one another; or 3) *connecting* two zones to each other. From the resulting eight possible combinations, three were neglected because of their impractical implications, as it is unlikely to host two adjacent circulation zones in a home or to subdivide an already cramped circulation zone. Table 1 illustrates how the remaining five conditions can be understood as spatial divisions within and in-between the two zone types. In practice, this mapping is more circumstantial as

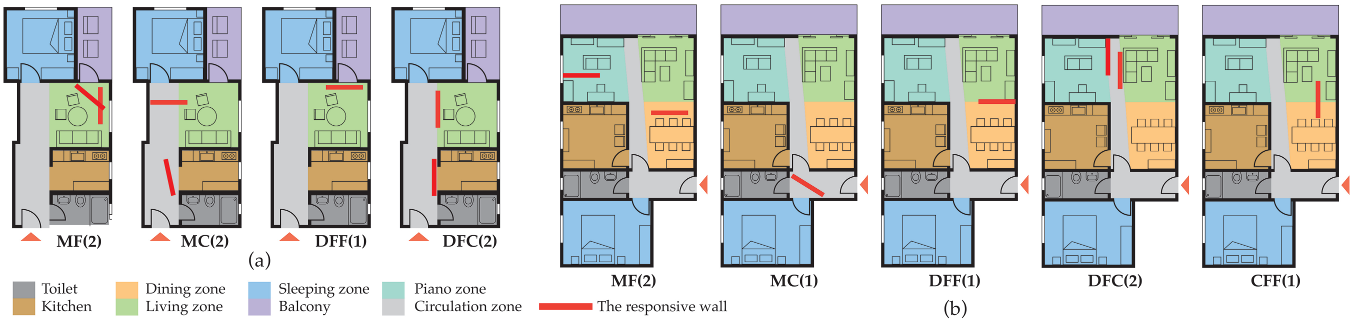

Figure 4: The addition of the wall for the deployed conditions within the homes of (a) P1+P2 and (b) P4+P5. Each diagram shows one or multiple wall locations that was used for each condition in the experiment as red lines. All experimental conditions are available in the Supplemental Materials.

Table 1: Experimental Conditions

Condition	Goal	Location of the wall
MF	Modify a functional zone	Inside the zone
MC	Modify a circulation zone	Inside the zone
DFF	Divide two functional zones	Aligned with the boundary
DFC	Divide a functional zone from a circulation zone	Aligned with the boundary
CFF	Connect two functional zones	Crosses the boundary

each floor plan cannot necessarily host all conditions. For instance, a home that does not feature two adjacent functional zones cannot host condition DFF and CFF, whereas condition DFC requires the circulation zone to be adjacent to a functional zone. To maintain a level of generalisability over all the homes, we applied each condition on two zones that hosted identical activities, i.e. eating or lounging. When the wall could be potentially positioned or directed in multiple valid ways, we preferred the more traditional architectural option, such as connecting the wall to the layout in DFF, or maintaining the symmetrical axes in MF or CFF. Figure 4 illustrates some of the discrepancies when the five conditions were deployed on the 1-bedroom apartments of participants P1+P2 and P4+P5.

3.4 Procedure

The researcher informed each participant about the research goals, asked them to read and sign a digital version of the ethical consent form, and report any expertise with other 3D, VR, AR or gaming platforms. During the first phase, the participant was asked to navigate inside an empty virtual environment to gradually learn the specifics of the navigation technique and the interface, and describe any noticeable differences between the virtual and the physical renditions of their homes. During the second phase, each participant was asked to observe the spatial implications of the responsive wall by selecting a predefined condition in the interface. After freely roaming around for about three minutes, the participant answered a questionnaire that popped up, or minimized it if she wanted to explore further. Once the questionnaire is answered, the researcher asked the participant to verbally explain her evaluation for each measure by comparing the current condition with those that appeared previously. The questionnaire included nine human experiential measures, taken from studies that measure the emotional quality of space (light/dark, cool/warm, quiet/lively) [42], architectural atmosphere (cozy/awestruck, sociable/private) [11, 33], the felt experience of technology (open/closed, expansive/confined) [34], the experience with intelligent space (welcoming/protecting) [63] and non-verbal human-robot communication (understandable/ambiguous) [48]. These measures were chosen particularly because they capture the wall not only as an architectural, but also as an interactive, technological and intentional element. Proposed metrics that cannot be embodied by a wall were excluded, such as colors and textures (atmosphere), exciting and frustrating (technological experience), friendly and helpful (intelligent space), or trustworthy and reliable (human-robot communication).

3.5 Data Acquisition and Analysis

The data thus included digital logs, questionnaire results, interview transcriptions, video recordings and qualitative observations made by the researcher. Second-level information was computed from the digital logs, including participant movement paths, time spent looking at the wall, and time spent walking around versus standing still. The audio-recorded interviews were transcribed and thematically analyzed to develop a structural understanding. The video feeds and observational notes proved useful in revealing behaviors that related the virtual to the physical experience. From the open-coding process, codes that presented spatial characteristics were labelled, rearranged and reevaluated iteratively into themes using affinity diagramming, which were then identified, reconsidered, split and merged multiple times by the two co-authors via group discussions.

4 RESULTS

We recruited a total of eight participants (four female, four male), originating from six different households and ranging between 23 to 30 years old (Mean = 26.88, SD = 2.09). Participants who lived together (P1+P2, P4+P5) were tested separately, but experienced the same set of conditions. Each experiment took between 51 to 70 minutes (Mean = 61.5 minutes, SD = 7.5), split between the first (Mean = 7.125 minutes, SD = 1.89) and second (Mean = 54.38 minutes, SD = 6.61) phase. Six participants used a laptop, two (P1, P2) used a tablet. When the connection became choppy (P1, P2) or was

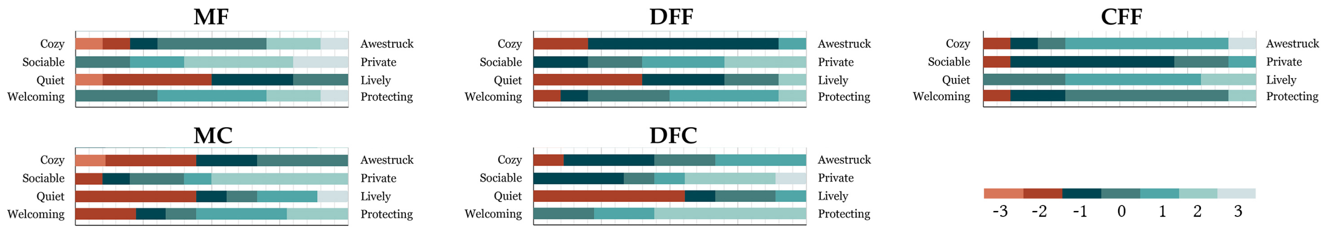

Figure 5: A subset of the questionnaire results that illustrate how the five conditions impact four human experiential measures of space. These results show that participants considered MF and DFF to be more *quiet*, MC felt *private* and *cozy*, DFC is *protecting*, and CFF is *sociable*. The full questionnaire results are provided in the Supplemental Materials.

Table 2: Participant demographics, home typology (1B: one bedroom apartment, S: studio), computer typology (T: tablet, L: laptop), background, and number of deployed conditions.

ID	Home	Computer	Age	Gender	Profession	MF	MC	DFF	DFC	CFF
P1	1B	T	28	F	Architect	2	2	1	2	
P2		T	27	M	Caregiver	2	2	1	2	
P3	1B	L	30	M	Office Worker	2	2		2	
P4	1B	L	26	F	PhD Student	2	1	1	2	1
P5		L	29	M	Musician	2	1	1	2	1
P6	S	L	27	F	PhD Student	1	1	2	1	1
P7	S	L	25	M	PhD Student	2	2	1	1	1
P8	S	L	23	F	Student	1	1	1	1	1

interrupted (P6), the researcher followed the verbal commands from the participant to navigate from the host computer. As shown in Table 2, the total study thus consists of 52 conditions from three 1-bedroom apartments and three studios, producing 9 hours and 43 minutes of interview time. Although our sample size seems relatively small, we believe that the variety of unique conditions (N=38) that were tested with real inhabitants of everyday homes allow us to scope our findings to small apartments particularly. The virtual environment seemed believable, since all participants immediately recognised their own home without discomfort. Participants with prior VR experience tended to actively explore the space (P5 was moving 69% of the total experiment, P7 = 73%) while beginners avoided to move (P3 = 37%, P8 = 21%).

Condition MF. When the wall altered the proportions of a functional zone, it generated a new space. Some participants felt "*private and safe*" (P5) in spaces that were wider horizontally than vertically, while "*higher*" and "*narrower*" spaces felt "*restrictive*" (P8) and "*confined*" (P6). When the wall restricted the visual field of a participant, the space was described to be "*more focusable*" (P7) when it obscured other parts of the home, except when the wall blocked the outdoor views through windows or balcony doors, which was considered "*stressful*" (P1) or "*suffocating*" (P2). When the wall increased the brightness of the functional zone by reflecting artificial ceiling light, it was considered to be more work-friendly because it afforded the participant to focus "*... it is less homely and much more suitable to focus and work*" (P6) in terms of privacy "*It feels like a private office space*" (P3) and efficiency "*It reminds me of the intense practice room in music school*" (P5).

Condition MC. When the wall appeared rotated compared to the surrounding walls, it formed a visible path to the entrance that was "*inviting*" (P1), "*welcoming*" (P7) and "*warm*" (P6) because it suggested a direction: "*... like you know which way to go to*" (P5). This positioning was interpreted as intentional, as participants used active verbs as: "*I think it is **telling** me not to go to the kitchen but to the living space*" (P2), "*It is **inviting** me to go towards the left side*" (P6). When the wall covered openings to outdoor spaces such as entrance doors, windows and balcony, it improved feelings of privacy "*It covers my private space if somebody comes to the entrance to have a quick chat*" (P7), while preserving the window as the source of light "*It is a shelter for changing clothes without having to draw the curtain*" (P1), and ventilation: "*I can leave the main entrance open for more ventilation and still have my privacy*" (P4).

Condition DFF. By disconnecting two functional zones, the wall increased the privacy in the open-plan studios "*...by covering the sleeping area when I have visitors*" (P8) and their living quality "*[by making] the apartment look more properly by separating the private parts from the living space*" (P7). Some disconnected zones also suggested flexible space usage as multiple co-located activities could take place simultaneously "*Now I can watch TV and she can have a Skype call without me distracting her*" (talking about his partner P4 - P5), or visitors can be hosted "*When my mother comes she can go to sleep early, and I can still work here without having to turn off the light*" (P8). A dividing wall augmented activities by covering "stuff" that was not deemed "relevant": "*The colorful bookshelf in the living space is distracting, so it is useful that the wall can separate that space from here*" (P4), by increasing the ergonomics of the space: "*This feels like a home cinema when it is separated from the working space. I think it is much more enjoyable*" (P5), or by avoiding ventilation issues: "*.. [it] prevent(s) the cooking smell from the kitchen to stain the sleeping area.*" (P2).

Condition DFC. When the wall separated the circulation zone, the functional space became more "*quiet*" (P3), "*secluded*" (P5) and offering "*more control and security*" (P2), by reducing the the entrance to the zone: "*It made this space into a small room with only one entrance, you will always know from which direction someone might be coming*" (P4) and its visual field "*... the corridor, so I will not be distracted when someone is walking there*" (P1). Yet, when the wall more severely disrupted the boundary between the two zone types, it generated an "*antisocial*" (P4) signal that the participant wanted "*to be kept alone*" (P1), and "*interrupted*" (P4) the flow between activities like cooking and dining that require access to multiple functional zones.

Condition CFF. Most participants could not recognise the purpose of CFF, as it created spaces that were "*random*" (P6) or "*hard to use*" (P5). When the wall crossed two functional zones, it often reduced the ergonomic conditions to use the furniture: "*I don't want to hit the wall when I stand up from the chair*" (P7), or move between zones: "*Sometimes I go to the fridge to grab a bite while working, but this is just too hard to move*" (P6). CFF sometimes obscured the visual field between multiple zones in impractical ways. such as to watch TV from a working table (P4) or to look through a window from the dining table (P8), making the space "*intrusive*" (P7) or "*not understandable*" (P6).

5 FINDINGS

We identified five architectural qualities that describe how the responsive wall influenced the experience of space.

Functionality reflects how the wall influences the affordances of a zone, by supporting original activities or by preventing or suggesting new activities to take place. When the wall moved *into* a functional zone severely (MF, CFF), it prevented activities by limiting its spatial proportions, blocking views, and reducing access to furniture, making the space "*random*" (P4-CFF), "*stressful*" (P3-MF) or "*purposeless*" (P7-CFF). When the wall was located *at the boundary* of a functional zone (DFF, DFC), it yet supported existing activities by reducing cumbersome spatial connections and visual fields, and by increasing the brightness and spatial consistency, which resulted in spaces that were "*quiet*" (P3-DFC), "*private*" (P6-DFC), "*focusable*" (P8-DFC) or "*enjoyable*" (P5-DFF). New activities were encouraged when the resulting spaces afforded new functionalities to take place, such as when a dining zone became a "*small office*" (P4-DFF) when it was separated from the living zonee (P4), or when a living zone became a "*private sleeping room*" (P1-DFC) by dividing it from the adjacent circulation zone.

Visuality reflects how the wall influences the visual fields that are afforded in a zone by covering existing views, creating new views, or preventing unwanted views from outside. By withdrawing views from a functional zone to other parts of the home (MF, DFF, DFC), the wall created spaces that allowed concentration, such as working (P8-MF), practising piano (P5-DFC), reading (P4-DFF) or playing games (P7-DFC). Directional views appeared when the wall created narrow spaces that were oriented towards openings such as windows or doors, which was deemed "*attractive*" (P1-MF) or "*focusing*" (P6-MF) because they emphasized "*a point to look at*" (P8-DFF), and because they blocked views from the outside, also increased privacy (MC).

Connectivity describes how the wall impacted the accessibility between zones, by disconnecting or changing existing, or opening new, connections. By withdrawing disturbing connections between zones (DFF, DFC), the wall created spaces that were "*meditating*" (P4-DFC) and "*secluded*" (P8-DFC), as it afforded to "*relax*" or "*get lost in a book*" (P5-DFF) in a "*personal space*" (P1-DFC). By modifying how a circulation zone (MC) connected zones to each other, the space became "*directional*" (P5-MC), "*inviting*" (P1-MC) and "*welcoming*" (P7-MC). By standing in front of a window or door, the wall provided additional privacy from the outside while yet allowing the door or window to remain open. It also increased the environmental comfort by increasing cross-room ventilation (P4-MC) or allowing natural lighting (P1-MC).

Materiality symbolises how the physical characteristics of the wall, including its shape, size, material and color, influences the experience through reflecting light, increasing airflow or bouncing off sound. When the wall reflected artificial ceiling lights or natural sunlight, the space became "*less homely*" and "*more office-like*" (P8-MF, P5-MF). When the wall was aligned with the main airflow direction, the (estimated) gain in ventilation made the space "*more breathable*" (P6-MC) with "*a cool breeze*" (P7-MC). When the wall formed an enclosed space surrounding a sound source such as piano or a loudspeaker, the space became "*bad acoustic for music*" (P4-MF) or "*not suitable for playing piano*" (P5-MF).

Uniformity conveys how the wall affords particular activities by hiding physical elements that are not relevant and by highlighting elements in the space that belong to one another. This quality was separated from Functionality and Visuality since its impact was mentioned explicitly by almost all participants (7/8) predominately in condition MF and DFF. A responsive wall can thus divide two functional zones (DFF) to generate a more coherent and less distracting space "*It is better to work when not seeing the bed*" (P8-DFF), and more functional "*It looks like it was made only for watching TV*" (P4-DFF). The wall also increased the apparent uniformity of space by covering elements that were not relevant to the activity it afforded, such as by hiding music sheets while reading (P5-MF), utensils (P6-DFF) or clothes (P8-DFF) while working, or a colorful bookshelf (P4-DFF) while watching movie.

6 DISCUSSION

6.1 Semi-Immersive Cross-Reality Evaluation

Although the semi-immersive cross-reality simulation methodology resulted from overcoming pandemic restrictions, it could potentially be generalised for evaluating prototypes of technologically complex spatial interventions within a wide range of contexts. Although the wall conditions were tested in different spatial settings, we were able to generalise our findings by reducing each setting into its architectural core elements that yet were still personally relatable to participants both visually (through observing the 3D simulation) and viscerally (through being present in the same space). As such, our approach seems to combine the already proven spatial experiential qualities of VR and AR [21, 22, 27, 51, 62] while maintaining the embodied and lived experience [37] of personal space. Various physical elements that were not virtually simulated were still influencing the spatial experience, as participants pointed to "stuff" such as "*distracting*" books (P4-DFF) or "*messy*" music sheets (P5-MF); tested the accessibility of a zone by measuring its physical dimensions (P6-MC); or estimated how the wall would affect the overall lighting by drawing a curtain (P2-MF). Participants also took into account serendipitous elements in their experience, such as how the sudden appearance of natural light made P5 feel "*meditating*" (MF), how the smell of food reminded P1 it was "*useful*" to separate the kitchen (DFF), and how a passing neighbour in the hallway prompted P7 that MC could make her home more "*private*". The

Table 3: The architectural framework for human-building interaction proposes how the provisional location of a responsive wall can provoke particular architectural qualities that in combination facilitate or hinder different atmospheres to occur.

Quality	Affordances	MF	MC	DFF	DFC	CFF
Functionality	Preventing existing activities	○ ◊				□ ○
	Supporting existing activities	■ ●	■ ▲	■ ● ▲	■ ● ▲	
	Suggesting new activities		● ♦		♦	♦
Visuality	Covering existing views	■ ▲	▲	■ ● ▲	■ ●	□ ○ ◊
	Creating directional views	●		●		
	Preventing unwanted views from outside	○ ▲ ◊	○ ▲		○ ▲	□ ○ ▲
Connectivity	Disconnecting existing connections	■ ○ ▲ ◊	▲ ◊	● ▲	■ ▲	
	Changing existing connections	●	■ ●		● ▲	□ ○
	Opening new connections		● ♦		♦	♦
Materiality	Reflecting light	■ ○	■	■	● ▲	●
	Increasing airflow	■ ●		■ ● ▲		●
	Reflecting sound	□ ○				
Uniformity	Separating zones into coherent spaces	■ ●		■ ●	■ ●	
	Hiding non-belonging elements	■		■ ●		■

□■ Focus atmosphere; ○● Relaxing atmosphere; △▲ Private atmosphere; ◊♦ Social atmosphere. ■ ● ▲♦ Faciliating; □ ○ △◊ Hindering.

unique floor plan of each home, however, made the methodology challenging to implement, while analyzing the large amount of qualitative data was time-consuming.

6.2 An Architectural Framework for HBI

As shown in Table 3, our architectural framework for HBI highlights how the provisional location of a wall can influence at least five distinct architectural qualities, which can be combined together to facilitate or hinder four functional types of atmosphere to occur. This framework was generated by mapping each of the conditions back to the architectural qualities, and then categorizing how each quality prevents, facilitates or suggests certain architectural affordances. We then augmented these mappings with what participants spontaneously described as the most suited activities that these conditions facilitate, grouped as four different architectural atmospheres, i.e. to focus, relax, socialise, or be left in private. As such, we define an atmosphere as the combination of architectural qualities that facilitate or hinder an atmosphere to be created.

Although our framework was derived by synthesising the verbalized self-reported experiences of participants, the derived qualities overlap with several architectural concepts. For instance, it is known that the visual characteristics of a space (i.e. Visuality) impacts the preference of people to work inside it [4]; that the spatial configuration and availability of furniture (i.e. Connectivity, Functionality) affects human behavior [50]; and that the color, light and texture of a space (Materiality) influences emotions [42]. Our framework augments these findings with a more holistic view of a single architectural element, recognising how a single wall position impacts multiple architectural qualities at once.

In turn, we suggest that our framework can also be used in the opposite direction, such as to determine potentially appropriate locations of a responsive wall when a particular atmosphere should be created. Figure 6 illustrates how a Focus atmosphere can be created for a simple, prototypical floor plan by applying different conditions. While each condition makes the space around the dining table more suitable to focus on work, the framework also suggests different (dis)advantages. While MF covers the view to the sofa (Visuality), reflects the natural light from the window (Materiality), and allows the circulation between the two doors (Connectivity), MC blocks the circulation (Connectivity) and view (Visuality) to a potentially disturbing door, and does not affect the lighting (Materiality). While DFF improves the coherence (Uniformity) of the dining zone, it disconnects it from the sitting zone (Connectivity), which is rendered completely inaccessible (Functionality). In turn, DFC blocks the dining table from the circulation zone (Connectivity) but still allows a wide visual field (Visuality).

Choosing the most appropriate condition forms a non-deterministic and designerly challenge, and depends on situational aspects that escape the framework. For instance, if the available artificial lighting is deemed insufficient to facilitate focusing, the wall could prioritize to reflect the natural light from the window (i.e. MF, DFF). A more technological approach might require a recommendation system that is aware of more contextual information such as the actual environmental condition (e.g. ambient light sensor) and the personal preferences (e.g. does focusing require bright or dimmed lighting for this occupant?). Accordingly, the architectural framework could thus be interpreted as a collection of design patterns [6], i.e. non-descriptive solutions that still require some mediate levels of architectural interpretation to fit the design situation at hand.

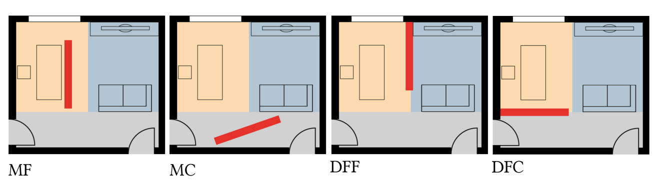

Figure 6: According to the framework, this basic floor plan can afford a Focus atmosphere by locating a responsive wall at at least four potential locations.

6.3 Architectural Challenges for HBI

6.3.1 Provisionality. Our findings show that the provisional presence of a responsive wall influences how the space it generates is perceived. For instance, participants tolerated uncommon spatial configurations: "*Although the space is small, I don't really feel confined* (...)" (P4-DFF), which they would normally resist in a static context: "*I would never build a static wall here* (...) *but the moving wall make it feel cozy*" (P7-MC). Although our framework might resemble classic architectural reasoning, it actually reflects the experience of a space that is able to dynamically adapt and respond. As such, our study contributes to current discussions on provisionality and temporality as relatively unexplored parameters in architectural design [5], which are promised to widen the functionality and expression of architecture [12] to achieve new kinds of experience [40].

6.3.2 Nudging Human Behavior. A responsive wall has the potential to nudge occupants to adapt their behavior, as participant P6 wanted to modify her seat to a new direction in DFF, when the "*messy*" and "*distracting*" kitchen that she previously avoided had been covered by the wall; or P4 would use the piano zone in his home to relax and read a book instead of practising piano because the wall created a "*meditating*" atmosphere with DFC. As such, our study provides the first self-reported evidence from common inhabitants to how responsive architecture could nudge behavioral changes in a domestic environment in ambient, subtle ways that people might not be aware of [3, 47], perhaps similarly to carefully-designed 'static' architecture [41].

6.3.3 Interactivity. Our framework expected participants to imagine a pro-active form of responsiveness. Consequently, participants voluntarily mentioned when and how they expected the wall to move, such as when an occupant moves "*It needs to adapt when I come close to the kitchen*" (P6-DFF), or alters her activity: "*When I want to practise the piano it can go there (...)*" (P5-DFC), but also when the environmental context changes: "*It should reveal the window when it is too dark*" (P2-MF). While different forms of spatial user tracking already exist [61], true pro-activeness can probably only be achieved when the intentions of the occupants can be predicted beforehand. Yet responsive architecture could also introduce intentional adaptations, such as by moving a wall gradually to change the atmosphere throughout the duration of a lunch, work session or night of sleep. While such scenarios would partly solve some issues about pro-active responsiveness, studying the impact of such long-term behaviors is challenging.

6.4 Limitations

We realise the study involved a relatively small participant cohort, yet believe that the contextual engagement of real-life inhabitants of small apartments on one side, and the wide variety of conditions on the other, provides a rich foundation that grounds the qualitative nature of our methodology. Whereas more participants would theoretically enable us to quantitatively 'validate' some of our findings to some extent, we think that the presented correlations in our framework would not significantly change as we only focused on spatial experiences that overlapped.

Some findings might be biased by various socio-cultural sensitivities that evidently impact the individual experience of space [32]. These sensitivities might be apparent in the architecture of the spaces themselves - which manifest a rather modernist and western view of student housing - as well as in how the inhabitants became accustomed to architectural expression in their personal lives. Although our participants were relatively culturally diverse with six different nationalities (i.e. BE, DE, EG, IN, SG, TW), our analysis only withheld experiences that appeared frequently and uniformly. This means that we recorded various inconsistent spatial experiences, such as while P1 (female, SG) described a semi-enclosed space generated by the wall in MF as "*safe*", P2 (male, BE) felt that the identical space was "*too confined*", or while P5 (male, DE) enjoyed the dimming, warm light when practicing piano, P6 (female, TW) expressed that it prevented her to focus.

The dimensions and materials of the responsive wall might restrict the validity of our framework to small-scaled spaces. Put differently, the spatial experience of the same wall located in a large, open loft space is most probably dissimilar from that inside a small, one-bedroom apartment or studio. Finally, we think that some findings that relate to environmental aspects like ventilation or privacy might be slightly biased and/or exaggerated due to the environmental conditions during the time of the experimentation, which took place in the summer of 2020. The relatively high ambient temperatures, which forced occupants to open their front doors to the common corridors in order to cool their homes, made participants sensitive to comfort issues. At the same time, these sensitivities also highlight the potential usefulness of responsive architecture in real-world, domestic settings.

In terms of methodology, the steep learning curve to navigate inside a 3D virtual simulation and some occasional networking latency issues introduced some level of unnecessary frustration for a few participants (P1, P6) that we were yet able to overcome by the friendly social conversing during the videoconference session.

7 CONCLUSION

This study demonstrated the potential to integrate architectural reasoning in responsive architecture towards reaching both functional and experiential goals. Through a remote, semi-immersive cross-reality methodology, we identified self-reported evidence of how a responsive wall influenced the experience of space of common inhabitants in their own everyday homes. We proposed an exploratory architectural framework that suggested how a responsive wall can be controlled to provoke particular architectural qualities that in combination could influence the architectural atmosphere of smaller-scaled domestic homes. The framework is not meant as a prescriptive rule set, but rather a starting point to discuss, measure and compare the relevance of architecture in HBI. Among other reflections, we discovered that the provisionality of the dynamic presence influenced how its space was perceived, and described its still untapped potential to nudge people to adapt their behavior.

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