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Designing and evaluating technologies to guide and nudge navigational decision-making

Designing and Evaluating Technologies to Guide and Nudge Navigational Decision-Making.

By

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Abstract

Sensory environmental cues influence our emotions and behaviours in ways beyond our consciousness. The way that these cues communicate information and influence behaviours and decisions implicitly has motivated the design of ambient technologies. With their goal of communicating information peripherally and without affecting the user's primary task, several cues have been used in their design to communicate information including light, movement and sound. In addition to communicating information peripherally, many ambient technologies have been designed to unobtrusively influence and alter various behaviours and decisions. However, little is known about how ambient technologies can be leveraged to implicitly influence and guide people's navigation decisions while exploring novel spaces. Such technologies are essential to facilitate navigation and provide seamless navigational guidance within indoor environments (e.g. museums) without negatively affecting the individual's primary task of exploration. In addition, these technologies are crucial in managing visitors' circulation in public spaces in cases of crowding or pandemics.

This thesis explores how can ambient technologies be utilised to unobtrusively facilitate, guide and nudge navigational decision-making while exploring unfamiliar environments. To deliver unobtrusive feedback in ambient technologies, I started by exploring the use of a low cue level that falls below the threshold of conscious perception (i.e. subliminal cues) and whether and how such cues can be used in ambient technologies to influence decision-making using the priming mechanism. The empirical findings showed that such subliminal cues are not suitable for use in ambient technologies and therefore, I explored next a higher cue level, which is a perceptible cue that influences behaviours and decision-making without awareness (i.e. supraliminal cues). These cues are delivered through the nudging approach. I particularly examined two nudging mechanisms: Social Norms, which uses supraliminal social cues in interactive floor interfaces and Salience, which uses supraliminal physical cues of shape-changing walls. I investigated how can such ambient technologies be designed to influence navigational decision-making using these nudging mechanisms and evaluated the influence of the designed technologies on navigation decisions. This thesis contributes to the area of Human-Computer Interaction (HCI) by providing novel insights into the use of subliminal cues in ambient technologies, the design of supraliminal social and physical cues in ambient technologies to influence navigation decisions and the impact of the designed technologies on navigational decision-making.

Dedication and acknowledgements

First and foremost, praise be to Allah the Almighty for all the blessings you have bestowed upon me. Thank you Allah for granting me the strength and courage to complete this journey.

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Author's declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's Regulations and Code of Practice for Research Degree Programmes and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: .... DATE: ....

Publications

Parts of the work presented in this thesis have been published in academic journals and conferences. I led all of the work in these papers and in this thesis, designed the studies, ran them, analysed the results and wrote the papers with the support of my supervisors.

Journal Papers

[J.1] Albarrak, L., Metatla, O. and Roudaut, A., 2021. Exploring the influence of subliminal stimulus type and peripheral angle on the priming effect. International Journal of Human-Computer Studies, 151, p.102631.

Conference Papers

[C.1] Albarrak, L., Metatla, O. and Roudaut, A., 2020, July. Exploring the Design of History-Enriched Floor Interfaces for Asynchronous Navigation Support. In Proceedings of the 2020 ACM Designing Interactive Systems Conference (pp. 1391-1403).

[C.2] Albarrak, L., Metatla, O. and Roudaut, A., 2021. (Don't) Mind the Step: Investigating the Effect of Digital Social Cues on Navigation Decisions. Proceedings of the ACM on Human-Computer Interaction, 5(ISS), pp.1-18.

Extended Abstracts

[E.1] Albarrak, L., Metatla, O. and Roudaut, A., 2019, May. An Exploratory Study for Evaluating the Use of Floor Visualisations in Navigation Decisions. In Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-6).

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Chapter 1

Introduction

THIS CHAPTER:

- Motivates the work conducted in this thesis and outlines the research questions.
- Presents the research approach, scope and methodology followed throughout this thesis.
- Introduces my contributions to knowledge and outlines the thesis structure.

1.1 Motivation

Our environments contain a rich set of sensory environmental cues that affect our behaviours and emotions unconsciously. By understanding how environmental cues influence behaviours, researchers have employed such cues to enhance individuals' health, performance and decision-making processes [146, 266, 320]. Advances in technologies made it possible to embed such cues within them in order to communicate information as well as to induce behavioural changes in individuals [337]. For example, ambient displays were envisioned as being all around us [337]. Such displays use unobtrusive environmental changes in shape, movement, sound, smell and light rather than using screens for information communication [337] and behaviour change [12, 251]. To date, numerous ambient technologies have been designed and developed to subtly influence and change behaviours including, health-related behaviours and purchase behaviour. However, there is a lack of ambient technologies that can utilise the various environmental cues to facilitate, guide and influence navigational decision-making within the built environment. This becomes essential for providing natural navigational guidance and facilitating making navigation decisions within unfamiliar indoor environments. Additionally, such ambient technologies are important for unobtrusively managing circulation of public space visitors, which helps in delivering the experience intended by public space designers without negatively affecting the visitors' exploration experience.

1.1.1 Environmental Cues and Their Influence on Behaviours

The impact of environmental cues is known to influence how we make inferences about the environment as well as our emotions and behaviours in ways beyond our consciousness [36, 197]. Sight, hearing, scent and touch are the main sensory channels that help us perceive and understand our surrounding environments. These sensory channels collect and process a collection of environmental cues that allow us to unconsciously make inferences about different aspects of the surroundings [36]. For example, pleasant ambient scents allow us to infer that the environment is welcoming and inviting. Similarly, we infer from certain colour schemes and lighting conditions that the environment is warm and friendly. Such inferences are a result of internal responses (i.e. emotional, cognitive and physiological) an individual experiences within an environment [19, 197]. In addition to these inferences, our behaviours within an environment are heavily influenced by the available environmental cues [197].

Different sensory environmental cues affect behaviours that involve decision-making such as spatial behaviours. Research has shown that ambient (e.g. lighting, colours), physical (e.g. corridor width, ceiling height, salient and moving objects) and social (e.g. presence/absence of people) cues of the environment influence individuals' navigation decisions [77, 78, 340]. Depending on how individuals perceive and respond internally to the cues, approach or avoidance behaviour is induced [197], which in turn affects their navigational decision-making. For instance, salient environmental cues such as vibrant colours or moving objects placed at one of the available path choices in indoor settings act as attractors (i.e. provide pulling power for visitors) and result in an approach behaviour [250]. Similarly, the presence of number of people in one of the path choices while exploring a museum, for instance, provides a pulling power for visitors to take that path choice.

Understanding how the environment influences individuals' emotions and behaviours has allowed researchers and designers to apply this knowledge to improve the quality of the surrounding environments. Environmental cues have been used in various environments to improve health, well-being, performance, learning outcomes as well as decision-making processes. For example, healthcare environments have shifted from a focus on functional design to a healing environment design that reduces stress, anxiety and promotes health and healing through environmental cues (See [85, 266] for a review). Also, different environmental cues have been used to improve performance and stimulate creativity in work and educational environments [55, 125, 157, 268, 320]. In retail store environments, marketers apply environmental psychology principles to increase customer dwell time and satisfaction and influence purchase behaviour [169]. Such conscious (intentional) design and structure of environmental cues to generate certain effects in individuals is known as *atmospherics* in marketing research [169] [1]. Finally, various environmental cues have been utilised to facilitate wayfinding in indoor environments (e.g. [76, 146, 147]).

1.1.2 Ambient Technologies for Communication and Behaviour Change

The way that sensory environmental cues communicate information to us silently and peripherally has inspired the design of ambient displays [337]. Envisioned by Weiser in 1996, such displays are a form of *Calm Technology*, which he described in his seminal work [329, 330] as an approach for calmly embedding technology into our lives (Ubiquitous Computing). This approach suggests that technologies should move back and forth between the periphery and centre of attention [330]. Design approaches for ambient displays achieve this vision by using unobtrusive ambient changes in temperature, light, colour, sound, scent, shape and movement, rather than presenting information using traditional GUI, to communicate information to users including, weather forecasts, stock prices and amount of human presence in buildings [227, 309, 337]. One of the early examples of ambient displays is the Dangling String which is an 8ft piece of wire that hangs from the ceiling and presents amount of network traffic through movement [330]. In addition, AmbientROOM [144], the Water Lamp and Pinwheels [75] utilised the architectural space and used light, movement, airflow and sound to communicate information subtly. Besides the capability of ambient technologies to communicate information peripherally, such technologies currently aim beyond that and extend to influencing and altering behaviours and emotions.

Ambient technologies have evolved over the last decade and have become a tool for modulating emotions and behaviours. Given the characteristics of ambient displays (i.e. conveying information in an unobtrusive way over a period of time), researchers have begun to explore them in the context of persuasive technology [12, 206]. Persuasive ambient technologies employ behaviour change approaches such as nudging [297] to induce positive behavioural changes in energy consumption, physical activity and sustainability. One approach to behaviour change using ambient displays, which showed a considerable effect on behavioural outcomes, is by raising awareness of themes underlying the data (e.g. [145, 206]). In addition, previous work have reported behavioural changes by using nudging approach with mechanisms such as social norms and salience [13, 155, 251]. For example, Rogers et al. [251] employed the salience mechanism and used an embedded LED light on the floor to nudge and influence movement patterns and motivate people to take the stairs instead of the elevator.

[1] Researchers have extended the use of atmospherics to include leisure and service environments such as malls and museums [102, 170, 202]

1.1.3 Research Gaps in Existing Literature

Although several ambient technologies have been designed to unobtrusively change behaviours such as purchase behaviour [155, 206], water intake [13], sedentary behaviour [103, 145], little is known about how ambient technologies can be designed to facilitate and alter navigational decision-making. Ambient displays have been shown to affect individual's spatial behaviour in the built environment [312]. For example, Rogers et al. [251] designed a display of interactive lights embedded in carpet tiles to alter movement patterns and guide people to use the stairs rather than the elevator. Though these findings uncover potentials of ambient displays in altering and influencing navigation decisions, they do not examine systematically how ambient technologies can be utilised and designed to unobtrusively influence, facilitate and guide navigational decision-making. In particular, the different levels of cues that can be used in the design of such ambient technologies. Such systematic examination would be beneficial for indoor public environments to influence and guide navigation decisions without negatively affecting the individual's primary task.

Influencing and guiding navigational decision-making using unobtrusive ambient technologies is crucial in many situations. For instance, such technologies, since they utilise our everyday objects and surfaces such as walls and floors, can be beneficial for providing seamless and natural guidance through spaces and for facilitating navigation and supporting people during the exploration of public spaces (e.g. museums and galleries). In this case, the design of the ambient technology and the cue type that it utilises guides users without affecting their exploration experience. In addition, public spaces can use such ambient displays to modulate and organise flow of visitors and achieve a naturally-controlled circulation. Managing visitors' circulation is important to achieve the public space intent in delivering a complete visitor experience (e.g. learning, encounters) [306]. This also becomes important with the current COVID-19 pandemic, where people are asked to follow certain routes and follow one-way systems to allow for social distancing. Since these instructions can get ignored frequently by people, ambient technologies designed to alter navigation decisions would influence and guide people while exploring indoor public environments in an unobtrusive way and without affecting the current task of space exploration.

The aim of this thesis is to explore how ambient technologies can be utilised to subtly influence, nudge and guide navigational decision-making while exploring indoor environments. This can be achieved by first understanding the role of environmental cues in influencing and shaping individuals' spatial behaviours in built environments and then investigating how such low-level cues can be leveraged in the design of ambient technologies that influence spatial behaviours.

1.2 Thesis Overview

Figure 1.1 shows an overview of the work conducted in this thesis. The different parts of the work and the order of examining them are described briefly as follows:

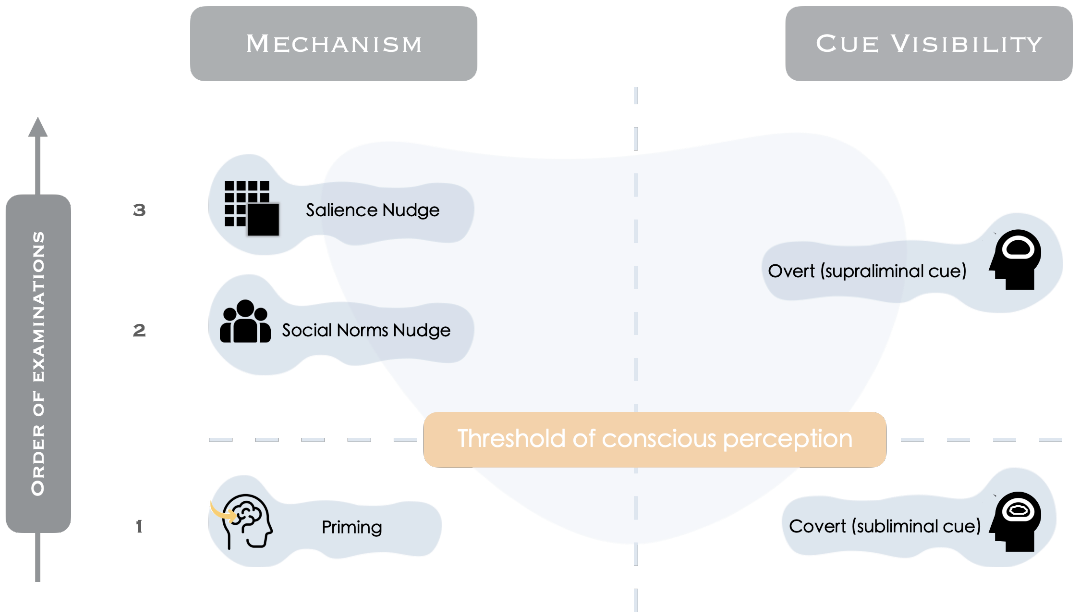


FIGURE 1.1. Research Approach.

1. In a preliminary study, I start exploring the feasibility of using low-level cues (i.e. subliminal cues) to influence decision-making. In controlled study, I use a three-monitor setup to explore the extent to which three types of subliminal cues, presented at two presentation durations, are effective at influencing decisions when presented in peripheral vision areas.

2. Based on the findings of the preliminary study which concludes that peripheral subliminal cues are not suitable for use in ambient technologies, I explore next a higher cue level (i.e. supraliminal cues, which are perceptible cues that affect behaviour without awareness) that influences decision-making through nudging mechanisms. The work presented in this thesis focuses on influencing navigational decision-making within the built environment, hence, it is essential to understand the factors (e.g. cognitive biases) that impact individuals' navigation decisions. One way to affect these decisions is through utilising the social norms bias and using the Social Norms nudging mechanism, which leverages people's tendency to follow other people or the traces they leave in an environment (i.e. social cues) when they navigate unfamiliar environments. In two studies, I explore how these social cues can be visualised, how they impact navigation decisions and how they are interpreted. Then, I examine how such social cues can be designed and embedded in floor interfaces to influence

navigational decision-making. Next, I examine in a lab study the influence of social cues, presented as footprints on an interactive floor interface, on navigation decisions.

3. In addition to the Social Norms mechanism, another way to influence navigational decision-making is through utilising the salience bias and using the Salience nudging mechanism, which leverages people's tendency to attend to prominent and salient features (i.e. physical cues) of the environment. I study in particular physical cues of shape-changing walls because of their movement quality that makes such technologies salient. In a online study, I examine how people experience such physical cues in Virtual Reality (VR) and how they impact people's perceptions. Then, I explore how physical cues of shape-changing walls can be designed to influence navigational decision-making. Following that, I investigate, in an online VR study, the impact of the designed shape-changing walls on navigation decisions.

1.3 Research Questions

There is a need for ambient technologies that can influence and guide people's navigation decisions without negatively impacting their navigation experiences. Therefore, the work described in this thesis addresses the following overarching research question:

How can ambient technologies be utilised to unobtrusively facilitate, guide and nudge navigational decision-making while exploring indoor spaces?

Ambient technologies have transformed architectural spaces into information interfaces, allowing information presented using such technologies to be perceived at the periphery of the human's attention without affecting the task at hand [337]. Such technologies have evolved and have been utilised, not only for information presentation, but also in implicitly inducing behavioural changes in individuals [145, 251]. Researchers have explored various approaches in order to change behaviours related to health (e.g. [103, 145, 175, 251]), energy consumption (e.g. [121, 163]) and shopping (e.g. [155, 156, 206]). In addition, researchers have examined using ambient technologies to influence navigational decision-making. For instance, Rogers et al. [251] presented Follow-the-Light, which is a playful floor LED lights that would trigger when approached with the aim of nudging and guiding people to take the stairs rather than the elevator. Although researchers have reported that the mere presence of ambient displays can influence navigational decision-making [312], exploring how ambient technologies can be used to subtly nudge and influence navigational decision-making to guide people in indoor settings remains limited.

Since this research question is highly exploratory, the following research questions aim to examine particular types of subtle and unobtrusive cues that can influence decision-making and explore whether they are suitable for use with ambient technologies. These unobtrusive cues include cues that fall below the threshold of conscious perception (i.e. subliminal cues) and perceptible cues that influence behaviour without awareness (i.e. supraliminal cues), as shown in Figure 1.1.

RQ1: To what extent can the priming mechanism that employ subliminal cues (i.e. presented below the threshold of conscious perception) be used to influence decision-making and be used in ambient technologies?

I investigate in this thesis (Chapter 3) the extent to which different types and presentation durations of subliminal cues are effective at influencing decisions when presented in peripheral vision areas. Cues that are presented below the threshold of conscious perception (i.e. subliminal cues) have the potential to influence decision-making [171]. Such cues have been used in HCI in order to enhance and enrich the interaction efficiency between humans and computers [218, 246]. While several efforts have examined the feasibility of subliminal cues at influencing decision-making and inducing behavioural changes in HCI (e.g. [11, 236]), these efforts have focused on delivering cues at the centre of the screen while the user is asked to focus on it. In addition, prior work have examined textual and graphical subliminal cues presented at specific durations, however, it remains unclear which type and presentation duration is more effective at influencing decisions when presented in peripheral vision areas. Understanding how subliminal cues work in the periphery is particularly important for ambient technologies where such cues can be used to implicitly communicate information or influence decisions without affecting the user's primary task.

RQ2: Can nudging with overt cues (i.e. supraliminal cues) be used as an approach to influence and guide navigational decision-making in ambient technologies?

In this thesis, I explore nudging as an approach to influence navigational decision-making. In particular, I examine the cognitive biases reported in the wayfinding literature and investigate how they can be leveraged in designing ambient technologies that nudge and influence navigational decision-making in a subtle way. Thaler and Sunstein [297] define nudging as *"...any aspect of the choice architecture that alters people's behaviours in a predictable way without forbidding any options or significantly changing their economic incentives (p.6)"*. With the nudging approach, cues used are usually overt (supraliminal cues) but people are unaware of their influence on them. Nudging exploits various cognitive biases that people have during decision-making to help them in making better decisions and changing behaviours [297]. For instance, by leveraging the *salience bias*, which is our tendency to focus on salient items while ignoring those that do not attract our attention [154], supermarkets can influence our purchase decisions and direct us towards healthier options by using bright and attention-grabbing packaging. In wayfinding literature, researchers have reported a number of heuristics and cognitive biases that individuals employ to facilitate their navigational decision-making within the built environment. For example, researchers have indicated that people have a tendency to follow path choices that have salient features such as paths that are wide and paths with more light [318, 319]. In addition, prior work have shown that people exhibit social norms bias while navigating unfamiliar environments and that they usually depend on others to make their navigation decisions [77, 78]. Such biases can be leveraged to influence people's path choice behaviour and guide them implicitly through the unfamiliar environment without negatively affecting their exploration experience. So far, few efforts have been made that use nudging as an approach in ambient technologies to influence navigation decisions [251]. Therefore, this work aims to explore this approach in depth and examine how ambient technologies can influence navigational decisions by leveraging the human's cognitive biases.

RQ2.1: How can ambient technologies be designed to influence navigational decision-making through nudging mechanisms?
This question investigates how nudging mechanisms and the biases they exploit (particularly social norms and salience bias) can be utilised in designing ambient technologies that influence navigational decisions implicitly. The cognitive biases and heuristics that people employ while navigating unfamiliar environments can be utilised in designing nudging interventions that can influence and guide navigational decision-making. While these biases and heuristics have been utilised in non-technological nudging interventions (e.g. using salient features at decision-points such as colours and bright light to attract people's attention [318]), there is a lack of technologies that can implicitly nudge, influence and guide navigational decision-making while also offer interactive experiences. Hence, this thesis explores the social norms and salience mechanisms and the cues they employ and investigates how technologies using these nudging mechanisms can be designed.

RQ2.2: How do ambient technologies designed using nudging mechanisms influence navigational decision-making?
With the previous research question, I focused on understanding the space and examining the design of ambient technologies that employ the social norms and salience nudging mechanisms to influence navigational decision-making. However, it remains unclear how such ambient technologies affect navigational decision-making. This research question investigates how the designed technologies, which use nudging mechanisms and their cues, impact navigational decision-making. Examining the impact of these ambient technologies helps in understanding the effectiveness of the designed technologies.

1.4 Research Approach

The examination of the overarching research question begins with a cue level that is imperceptible and falls below the threshold of conscious perception. The reason behind starting with such a low-level cue is their ability to influence behaviours unconsciously without affecting the primary task. Recently, HCI researchers have begun to investigate this type of cue (i.e. subliminal cues) as an additional channel for information communication without negatively affecting current critical tasks. This led to the first research question (RQ1) where I questioned whether this type of cue can be used to influence decisions when presented in peripheral vision areas and whether it can be used in ambient technologies. To answer this question, I conducted a preliminary study to explore whether subliminal cues presented in peripheral vision areas would influence decision-making in general. The findings of this study showed inconsistencies in the influence of the subliminal cues on decision-making which led to the conclusion that peripheral subliminal cues are not suitable for ambient technologies.

Based on these findings, this research explored next a higher cue level; supraliminal cue which is a perceptible cue that affects and alters behaviour without awareness. One way to utilise such cues is to use nudging as an approach to influence behaviour without awareness. Nudging takes advantage of the cognitive biases that humans have to influence behaviours. Since this thesis focuses on influencing and guiding navigational decision-making, it is crucial to understand and examine the factors that influence people's path choice behaviour in indoor public spaces such as museums and galleries. These provide us with a set of cognitive biases and heuristics that people use to facilitate the complex task of navigation, which can be leveraged in the design of ambient technologies. I identified two biases that can be exploited in the design of nudges that influence and guide navigational decision-making including, social norms bias and salience bias. Social norms bias occurs when individuals follow behaviours of other people while making their navigation decisions. This can happen asynchronously (e.g. following physical traces left by other people, i.e. social cues) or synchronously (e.g. following people who are present at the same time and space). Salience bias occurs when salient features (e.g. colours, size or movement) in the environment attract people's attention and affect their decisions while navigating indoor spaces (i.e. physical cues). In this thesis, I explore these social and physical supraliminal cues, design nudges that leverage these biases and utilise them in ambient technologies to influence navigation decisions (RQ2.1) and examine their impact on navigational decision-making (RQ2.2).

1.5 Research Scope

There are three relevant aspects with respect to which the scope of this thesis is limited: 1) Cue level, 2) Cue modality and 3) Behaviour change approach. I focus in this research on examining low-level cues that can influence and alter navigational decision-making without requiring too much attentional demands. Embedding such low-level cues in ambient technologies is particularly important for providing support for users without interrupting their primary tasks (e.g. navigation).

To narrow the scope of this research, I focus my systematic examination on visual cues. The reason for this focus is that using such visual cues in ambient technologies have already been shown to influence spatial behaviour (e.g. [251, 312]) and hence this research builds on this existing knowledge and extends it to an in-depth examination of low-level visual cues that influence navigation decisions.

Furthermore, I focus in this thesis on behaviour change interventions that utilise the automatic mind rather than the reflective mind. Reflective approaches (e.g. Transtheoretical model and Theory of Planned behaviour) are multi-factor behaviour change methods that require reflective motivation from the individual about changing behaviour (i.e. conscious evaluation and planning), whereas automatic approaches are unobtrusive, single-factor approaches that target the automatic mind and do not require prior motivation (e.g. subliminal priming, nudging) [2, 201]. Automatic approaches are thus more suitable in inducing behavioural changes in spatial behaviour at the point of decision-making without negatively impacting the individual's primary task. Therefore, in this thesis, I focus my exploration on the approaches that leverage our automatic mind such as subliminal priming and nudging.

1.6 Research Methodology

To investigate how ambient technologies can be utilised to influence navigational decision-making unobtrusively, I used a mixed-methods approach. This methodological approach allows researchers to utilise the strengths of both quantitative and qualitative approaches, which provides a better understanding of the research question rather than either of each alone [73, 74]. Mixed-methods approach deals with pragmatism as the main philosophy, which explains that researchers should use the approach or a mixture of approaches according to their suitability to the research question [149, 150]. In HCI, mixed-methods approach is common and has been successfully employed to address multidisciplinary HCI research questions [251, 304, 310]. The interdisciplinary nature of this research requires such an approach that can be used to design and evaluate ambient technologies that alter navigational decision-making. Therefore, to answer the raised research questions, I use the following qualitative and quantitative methods:

Experimental studies investigating the relationship between an independent variable (i.e. Cue type) and dependent variable (i.e. the resulting behaviour). These studies took place in controlled settings and provided quantitative and/or qualitative data about the relationship between these variables. This thesis presents three experimental studies examining the influence of: 1) Subliminal cues on decision-making (Chapter 3); 2) Social cues on navigational decision-making (Chapter 5) and 3) Physical cues on navigational decision-making (Chapter 7).

Interviews providing qualitative data describing participants' experiences of specific technology designs and reflections on completed tasks. This thesis presents one-to-one structured and semi-structured interviews in Chapter 4, Chapter 5 and Chapter 6.

Design sessions conducted with future users to examine how can ambient technologies be designed to influence navigational decision-making through the social norms and salience nudging mechanisms. Design sessions examining the social norms mechanism focused on designing for floor interfaces (Chapter 4) whereas design sessions examining the salience mechanism focused on designing for shape-changing interfaces (Chapter 6).

The justification of each method is explained in more detail in their respective chapters.

1.7 Contributions

The work presented in thesis contributes new knowledge to the HCI field in general, and particularly to the areas of ambient and persuasive technology. A summary of my contributions is listed below:

1. A new understanding into the use of peripheral subliminal cues to influence decision-making and whether these cues can be used in ambient technologies. In a controlled study (Chapter 3), I investigate three types of subliminal cues when presented at thirteen peripheral visual angles and tested using two presentation durations. I demonstrate that there is significant effect of particular types of subliminal cues on decision-making at specific visual angles and presentation durations. However, the inconsistency in these findings makes subliminal cues not suitable for influencing decision-making in ambient technologies.

2. An understanding of the use of two nudging mechanisms (Social Norms nudge and Salience Nudge) and how the cues they employ affect people's perceptions.

   2.1 I provide insights into how social cues can be visualised, how they impact navigation decisions when presented on the floor and how people interpret them. In a study, I assess six different visualisations of navigation traces. I show that direct and intuitive visualisations (i.e. footprints) are well-suited to represent navigation traces of other people.

   2.2 I provide a novel understanding into how physical cues of shape-changing walls impact people's perceptions. In a VR experience showing different types of shape-changing walls, I demonstrate that shape-changing walls can impact people in many ways including, provoking positive and negative emotional reactions and inducing pleasant and unpleasant sensory illusions.

3. Guidelines and design recommendations for designing ambient technologies that influence navigational decision-making in two nudging mechanism.

3.1 I provided a set of guidelines for designing history-enriched floor interfaces that influence and nudge navigation decisions. By carrying out design activities with participants, I demonstrate that using realistic visualisations in the design of such floor interfaces is preferred.

3.2 I provide useful insights into designing shape-changing walls with minimal intrusiveness levels as well as insight into designing them to impact navigational decisions. I show that using certain types of change (e.g. Amplitude) can make designs more intrusive. Also, I demonstrate that shape-changing walls can be designed to nudge navigation decisions by using encouraging nudge designs and discouraging nudge designs.

4. An evaluation of the impact of the designed ambient technologies on navigational decision-making.

4.1 I provide a new understanding into how social cues, presented as footprints on an interactive floor interface, impact navigation decisions. In a lab evaluation study, I show that the impact of social cues on navigation decisions depends on how the cues are interpreted.

4.2 I provide novel insights into the effect of different types of shape-changing walls on navigational decision-making. In an online evaluation study in VR, I demonstrate that certain types of shape-changing walls can attract people into taking path choices with shape-changing walls, while other types can deter people from following them.

1.8 Thesis Structure

This thesis consists of eight chapters, as shown in Figure 1.2. These chapters are structured as follows:

Chapter 2 provides a background to key areas needed to understand this thesis and discusses related prior research. This chapter starts the first section by introducing environmental psychology and the theories that examine how the environment affect individuals and then discussing in more depth the cues that influence navigational decision-making in indoor public environments. The chapter then presents background on dual process theories of decision-making (i.e. automatic mind, reflective mind) and discusses the approaches to behaviour change with more focus on approaches that utilise the automatic mind. Furthermore, the chapter describes relevant previous research, which includes an overview of calm computing and ambient technologies and a review of prior research on persuasive ambient technologies that leverage the automatic mind and ambient technologies designed to implicitly influence movement patterns. The chapter also describes the approaches that public displays use to attract the attention of passers-by and influence their

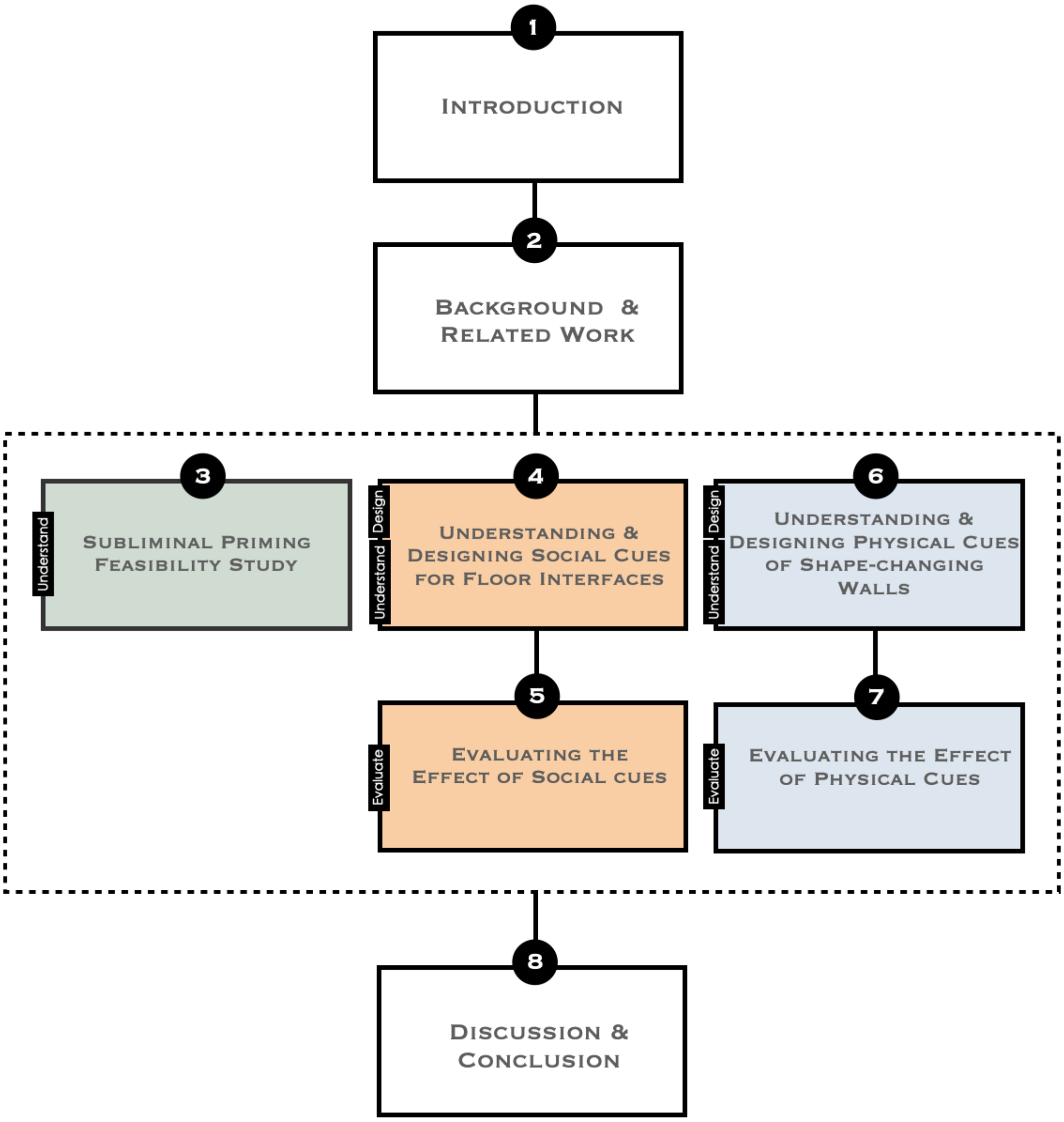


FIGURE 1.2. Thesis structure.

spatial behaviour. Computer vision technologies designed to influence spatial behaviour are also described.

Chapters 3-7 describe the empirical work that was conducted to answer the raised research questions.

Chapter 3 describes a preliminary study I conducted to explore the feasibility of using subliminal cues to influence decision-making in ambient technologies. I investigate the extent to which different types and presentation durations of subliminal cues are effective at influencing decision-making when presented at peripheral vision areas.

Chapter 4 presents two studies that explore how social cues can be designed to influence and nudge navigational decision-making using the social norms nudging mechanism. Study 1 explores how to visualise, integrate and interpret such social cues in floor interfaces. Study 2 presents one-to-one design sessions with potential users that explore how the selected visualisation could work in practice and examine the challenges identified in Study 1.

Chapter 5 describes a lab study conducted to investigate the impact of the designed social norms nudge (i.e. presenting social cues, in the form footprints, on an interactive floor interface) on navigational decision-making. The study examines and compares participants behaviours in control and intervention conditions during two tasks: free exploration of the space followed by search.

Chapter 6 presents an online study conducted in VR to explore how physical cues can be designed to influence and nudge navigational decision-making using the salience nudging mechanism. Due to their saliency, the study uses shape-changing walls as physical cues that can influence navigation decisions. The study explores how people experience different designs of shape-changing walls in VR and conducts one-to-one design activities to explore how such physical cues (i.e. shape-changing walls) can be designed to influence navigation decisions with minimal intrusiveness levels.

Chapter 7 describes an online VR study that explore how the salience nudge that uses the designed shape-changing walls (in Chapter 6) influences navigational decision-making. The study examines four different types of shape-changing walls in an exploratory navigation scenario.

Chapter 8 discusses how the work presented throughout this thesis answers the research questions and highlights my contributions. The chapter concludes by discussing directions for future work.

Chapter 2

Background and related work

THIS CHAPTER:

- Provides an overview of the models that help in understanding the human-environment relationship and discusses the environmental cues that impact spatial behaviour.
- Discusses dual-process theories of decision-making and describes approaches to behaviour change that leverage the automatic mind.
- Discusses relevant existing technologies, including ambient and persuasive technologies.

I have published parts of this chapter in [J.1], [C.1], [C.2] and [E.1].

2.1 Introduction

The aim of this thesis is to explore how ambient technologies can be utilised to unobtrusively guide and nudge navigational decision-making while exploring indoor spaces. This chapter reviews related research that lays the foundation for this thesis. It starts with an overview of environmental psychology and the theoretical models that help in understanding the human-environment relationship. It also discusses various environmental cues that impact path choice behaviour, including ambient, physical and social cues. Since the focus of this work is on automatic approaches to change behaviours, it is essential to first understand the fundamentals of this

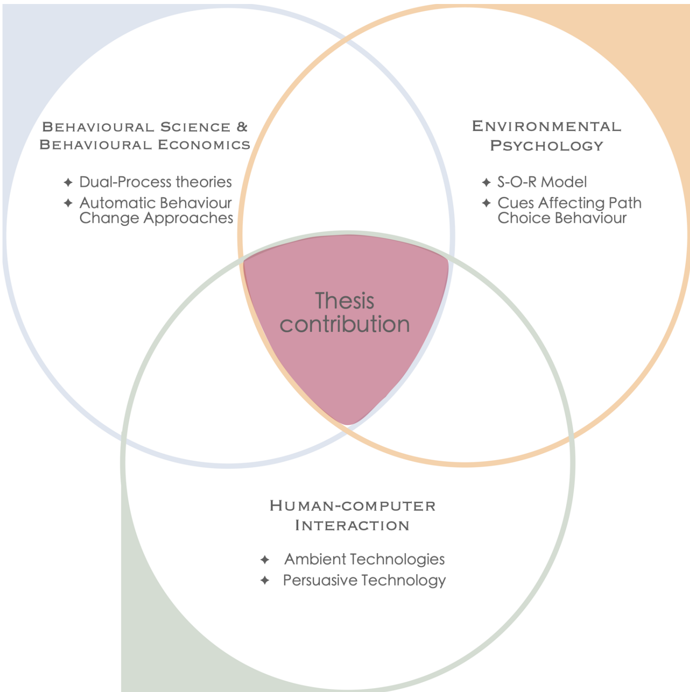


FIGURE 2.1. Venn diagram illustrating where this thesis contribution sits compared to related research.

approach along with the contrasting approach. Therefore, the chapter discusses next the dual-process theories of decision-making and explains the two behaviour change approaches including, reflective and automatic approaches. It also discusses in more depth particular mechanisms such as subliminal priming and nudging. Next, the chapter moves to discuss developments in ambient technologies research and the different evaluation methods. Then, the chapter reviews persuasive technologies and the current approaches to design them, focusing more on persuasive ambient technologies. I then highlight the limitations of existing persuasive ambient technologies and the need for ambient technologies that subtly influence navigational decision-making in order to support individuals while exploring novel indoor environments. Finally, the chapter concludes by discussing relevant research from the computer vision field, which uses sensory illusions to induce changes in walking directions. Figure 2.1 describes where this thesis contribution sits compared to the three research areas examined.

2.2 Environmental Psychology

Environmental Psychology is an interdisciplinary area that examines the relationship between people and their environment (natural and built environments) [72]. In particular, the field studies how and why environments affect individuals' behaviours, experiences, health and well-being, how individuals influence the environment, and how individuals can be encouraged

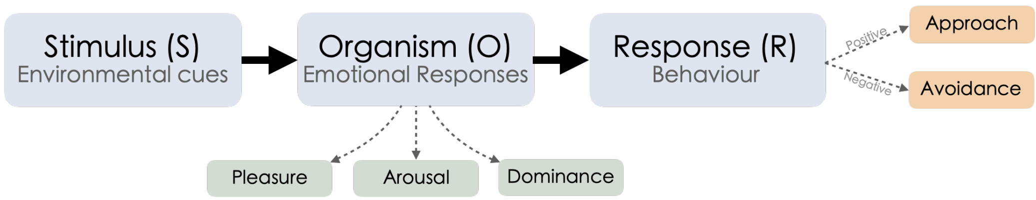


FIGURE 2.2. Mehrabian and Russell theoretical model (S-O-R) [197].

to change behaviours that negatively affect the environment [284]. Two of the main topics discussed in environmental psychology are spatial behaviour, wayfinding and the factors that affect them within the built environment [26] and the design of physical qualities and how they are experienced in the built environment (e.g. public spaces, workplaces and schools) [94]. This section starts with an overview of the main theoretical models in environmental psychology that are essential to understand how the environment affects humans and describes typologies for environmental cues. It also discusses the applications of the Stimulus-Organism-Response (S-O-R) model in various domains. Finally, it concludes with a discussion of the environmental factors (cues) that affect spatial behaviour within built environments, which is the focus of this thesis.

2.2.1 Theoretical Models in Environmental Psychology

One of the most important models in environmental psychology that is used to understand the reasons behind people's behaviours is the Stimulus-Organism-Response (S-O-R) model [197]. S-O-R proposes that Stimulus (S) from the environment, affects individuals' internal evaluations (O), which in turn impact behavioural responses (R), as shown in Figure 2.2. Stimulus (S) includes all the possible environmental cues, which is expressed as the *information load* (i.e. the degree of novelty and complexity within an environment). An individual (O) experiences emotional states, which can be described using three dimensions: pleasure, arousal and dominance, that mediate behavioural responses within an environment [197, 249]. Behavioural responses (R) towards an environment can be either approach or avoidance behaviour [197]. Approach behaviours include all the positive behaviours that can be directed towards an environment such as a desire to physically stay, explore or return to the environment, whereas avoidance behaviours include all the negative responses that can be directed towards an environment such as a desire to leave, not to explore or not to return to the environment [197, 249, 280]. The S-O-R model has two main limitations; first, it lacks a classification of the environmental cues and second, it limits the individual's internal responses to emotional responses.

To address these limitations, researchers (examining retail and service environments) have developed a typology for environmental cues. Typologies developed by Baker [18] and Bitner [36] are the most commonly used models for describing environmental cues. Baker [18] presented a taxonomy that consists of three main types: ambient, design and social. Ambient cues include cues that affect non-visual senses and tend to influence the subconscious such as temperature, noise levels, odours, air quality and music, whereas design cues are visual and can be perceived consciously such as functional and aesthetics components of the environment (e.g. physical elements: architecture, furniture and layout) [18]. The social cues are the people element of an environment (e.g. number of people, presence of others, crowding) [18, 20].

Similarly, Bitner [36] developed a model that examines the environment-user relationship in service organisations and presented three main types of environmental cues: ambient, space/function, and signs, symbols and artefacts. Ambient cues include background features of the environment such as lighting, colours, noise, music, temperature and scent. Space/function cues include the layout of the furniture, machines and equipment within an environment, their size and shape, and their ability to facilitate the accomplishment of goals. Signs, symbols and artefacts cues include implicit and explicit forms of communications such as signage, artworks and quality of materials used in construction. The framework (Figure 2.3) also proposes that these environmental cues are perceived by individuals and that they can respond to the environment cognitively (e.g. beliefs, classification) and physiologically (e.g. pain, comfort) as well as emotionally (e.g. mood, attitude). These internal responses lead to behavioural responses of either approach or avoidance behaviours.

2.2.2 Application of S-O-R model

The S-O-R model was first developed as a general environmental psychology model, but it has been adapted later and applied in particular settings such as retail, service and entertainment. For example, researchers have applied the principles of environmental psychology and behavioural economics to retail and marketing settings as a way to influence purchase decision-making [303]. In the marketing domain, Kotler [169] defined the effort of designing buying environments in order to produce emotional responses in buyers that nudge and increase their purchase likelihood as *atmospherics* and identified its use as a marketing tool. Kotler also described it as a silent language in communication [169]. The atmosphere of an environment can be designed to communicate a message such as the environment's intended users, grab attention by using colours and motion that make it more salient or to create certain emotional effects through the use of sounds and colours [169].

Different types of atmospherics (environmental cues) have been examined to influence consumer behaviour, emotions and experiences, including visual (e.g. colour, brightness) (e.g. [27, 33]), auditory (e.g. volume)(e.g. [168, 209]) and olfactory (e.g. scent) (e.g. [88, 280]) cues. For example, manipulating ambient light brightness have been shown to affect food choices in service environments such as restaurants and coffee shops [33]. Also, background music have been used to stimulate shoppers, induce consumer's shopping behaviour and increase time spent in retail settings [168, 204, 209] and influence customers behaviours in restaurants [205]. In addition, olfactory atmospherics cues (e.g. smell of freshly baked bread, roasted coffee or chocolate)

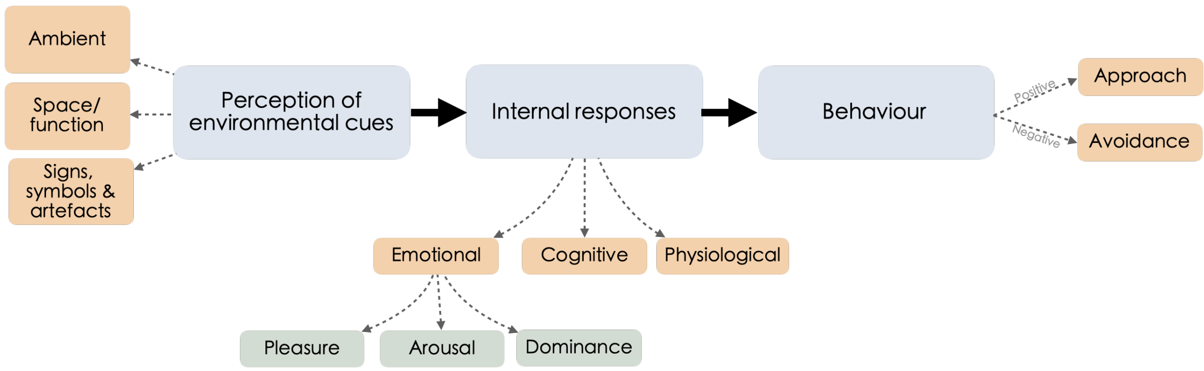


FIGURE 2.3. Bitner's environment-user relationship model in service organisations [36].

have be shown to entice customers' purchase behaviour and to increase time spent within the environment [88, 120, 275, 280].

While the majority of the atmospherics research has been conducted in retail settings, several researchers have examined their effect in a specific type of service environment such as museums, art galleries and zoos [40, 102, 135, 170]. For example, researchers have indicated that environmental cues (atmospherics) in museum settings play an important role in the overall visitor experience [102, 252]. In particular, such environmental cues have been shown to impact visitor affect and behaviour [170]. In addition, Bonn et al. [40] studied four different settings (museum, aquarium, arts centre and zoo) and showed that environmental cues, including ambient (e.g. colours, lighting), design (e.g. layout, traffic flow) and social (i.e. evaluating the service employees) cues, have a direct influence on revisit intention and intention to recommend. Also, researchers have noted that environmental cues within a museum context (e.g. design and content) play a crucial role in influencing the learning experience of visitors [135]. Moreover, environmental cues (i.e. design cues such as the architectural layout and arrangement of objects) have been shown to affect spatial behaviours of visitors within museums [62, 306].

2.2.3 Impact of Environmental Cues on Path Choice Behaviour

While personal factors such as personal preferences [95] and walking habits (e.g. turning right) [34] can play an important role in individual's spatial behaviour. Research has also shown that various environmental cues have a considerable effect on spatial behaviour, particularly path choice behaviour, in indoor public settings such as museums, art galleries and shopping malls [10, 131, 250, 267, 293, 319]. By using Baker's typology of environmental cues, which includes ambient, design (i.e. physical) and social cues, I describe below how different variables within each of these cues impact path choice behaviour in built environments.

2.2.3.1 Ambient cues

Ambient cues include cues such as environmental colours, light, odours and music. Research has shown that ambient light works as an attractor (i.e. attractors are elements of the environment that direct spatial behaviour towards them [95]) and can have a noticeable influence on individuals' spatial behaviour [10, 293, 319]. For example, Vilar et al. [318, 319] examined path choice behaviour within a virtual environment and found that individuals choose path choices with more lighting, even when other physical cues (e.g. wide path choice) are present. In addition, Antonakaki [10] reported that people gravitate towards bright spaces. Researchers have also examined how colour and light influence spatial behaviour [196] and noted that these variables can be used to increase the legibility of a space [130]. Furthermore, odours and sounds can be considered as attractors as they have been shown to affect spatial behaviour and invite individuals to the odour and sound source in urban public space [16].

2.2.3.2 Design (Physical) cues

Design cues are physical elements of the environment such as architecture and furniture as well as the layout of the space. Research has shown that physical and architectural features of the built environment such as the location of entrance and exit, length of the path and position and number of doors [131, 250, 267] can influence path choices. In this case, people select direct and distance-minimising paths without being fully aware of their choices [131]. Bitgood [34] referred to this strategy as "the general value principle", which states that the value of an experience is calculated as a ratio between benefit (learning, satisfying curiosity, etc.) and cost (time, effort). Other architectural features that have been found to influence path choice behaviour include the width and ceiling height of the path [317–319]. In addition, salient and attention-grabbing objects that offer qualities of beauty, curiosity, or educational value along the path have been shown to act as attractors (i.e. approach behaviour) [250]. An object is considered salient if it is different from its surroundings and catches one's attention [166, 219]. The difference can be expressed in terms of perceptual qualities such as size, colour, shape, pattern, texture, light or movement [48]. These attractive features create a bottom-up attentional capture that affects people's path choice behaviour [35, 48]. Also, research has shown that the overall plan configuration and the layout of the space has a considerable impact on individuals' spatial behaviour in the built environment [62, 86, 240].

2.2.3.3 Social cues

Social cues include actual people or the traces they left within an environment. In many decision-making contexts, observing other people and their interactions and actions can have an impact on our behaviours [17]. In particular, research has shown that the presence/absence of other people, their number and the actions they performed in the past have a noticeable impact on individual's navigational decision-making during exploratory tasks [77, 78, 340]. The influence that other people have on our spatial behaviour, particularly wayfinding, is described by Dalton et al. [77] as *social wayfinding*. They classify social wayfinding into strong and weak social wayfinding. Strong social wayfinding involves intentional communication between co-navigators (i.e. sender and receiver) whereas weak social wayfinding involves indirect and unintentional communication between co-navigators (i.e. both the sender and receiver are not aware of offering the information and using the cues respectively) [77]. These two types have been classified further, based on the time frame in which they happen, into synchronous and asynchronous social wayfinding [77]. The synchronous type occurs when the sender and receiver are co-present in time and space whereas the sender and receiver are not present at the same space and time in the asynchronous type [77]. For example, the synchronous strong type occurs when individuals collaborate to make navigational decisions, whereas the synchronous weak type occurs when individuals use other people, who share the same space, as cues. In addition, the asynchronous strong type happens when individuals follow given route instructions, while the asynchronous weak type occurs when individuals use physical traces that other people have left (e.g. traces in the park) to make their navigational decisions.

2.2.4 Summary

In this section, I presented an overview of the environmental psychology field and its main theoretical models that aim to understand the human-environment relationship (i.e. Mehrabian et al. [197] and Bitner et al. [36] models). I discussed how these models and the environmental cues they identify are applied in various contexts. Then, I particularly focused on discussing how such environmental cues influence spatial behaviour. Although the aforementioned prior work showed that different types of environmental cues (non-technological interventions) can be used to influence and alter people's behaviours and decisions, it remains unclear whether and how technological interventions that employ such cues can be used to influence behaviours and decisions, particularly navigational decision-making.

2.3 Behavioural Economics & Behaviour Change

Behavioural economics integrate economics principles with behavioural science to understand how people make their decisions [49, 245]. Observations of human behaviour have led behavioural economists to assume that individuals are irrational in decision-making even though the information needed to make better decisions is available [245]. Behavioural economics researchers have employed concepts of dual-process theories to improve decision-making models [153]. With these theories, researchers distinguished between two systems: reflective system and automatic system [153]. While both systems always cooperate, each of them processes information differently. For instance, the reflective system is analytic and slow, whereas the automatic system is heuristic and fast. By targeting the processes of either of these systems, behaviours of individuals can be altered and adjusted. There are two approaches to change behaviour based on these systems: reflective behaviour change approaches and automatic behaviour change approaches. In this section, I discuss each of these approaches and the theories within each approach.

2.3.1 Dual-Process Theories of Decision-Making

Dual-process theories distinguish between two modes of information processing in decision-making and problem solving: System 1 and System 2 [58, 153, 285] (See [97] for a review). In behavioural economics, Kahneman [153] presented a generalised dual-process theory and described System 1 as automatic, fast, heuristic and requires little or no effort, whereas System 2 as controlled, slow, analytic and effortful. System 1 operates unconsciously while System 2 operates consciously. Both systems are always active and are interacting with each other continuously [2]. System 1 is responsible for generating intuitions, impressions and feelings, which are provided as suggestions for System 2. System 2 turns these suggestions into explicit beliefs and actions [153]. An example of an activity performed by System 1 is driving, whereas activities that require attention such as solving a mathematical equation or filling out a form are performed by System 2.

In addition to the dual-process theories of decision-making and problem-solving, there are a number of dual-process theories that focused on persuasion and behaviour change such as the Elaboration Likelihood model [234] and the Heuristic Systematic Model [57]. Such models distinguish between two routes for persuasion; central (or systematic processing) route and the peripheral (or heuristic processing) route. The central route involves careful consideration and reflection of the message, whereas the peripheral route processes messages without careful consideration(e.g. through the use of heuristics and shortcuts). Within each of these routes, there are a number of behaviour change approaches that attempt to influence and change behaviours.

A behaviour change approach is any technique that is capable of impacting individuals and their behaviours [15]. There exists a plethora of theories and approaches that attempt to understand and change behaviour (e.g. [3, 112, 297]). Some of these approaches, referred to as *reflective approaches*, require motivation, ability and conscious reflection in order to be effective, whereas *automatic approaches* do not require such conscious monitoring and are less reliant on motivation and ability [2, 87]. Reflective approaches depend on System 2 while automatic approaches depend on System 1 [87].

2.3.2 Reflective Behaviour Change Approaches

Among the behaviour change theories that explain behaviour change and provide basis for designing interventions (that require reflective motivation) are the Transtheoretical Model (TTM) and the Theory of Planned Behaviour (TPB). The Transtheoretical Model, also known as the Stages of Change, requires individuals to have motivation and willingness to change behaviours [112]. It uses stages of change: Pre-contemplation (no intention to change behaviour in the near term), contemplation (individual intends to change behaviour within the next six months), preparation (individual intends to take action in less than a month with few behavioural steps taken), action (individual has changed behaviour for less than six months) and maintenance (individual has changed behaviour for more than six months) [112]. The Theory of Planned Behaviour links individual beliefs to behaviours [3]. It posits that behaviours result from behavioural intentions, which in turn are determined by three components: attitude towards the behaviour (i.e. favourable or unfavourable evaluation of the behaviour to change), subjective norms (i.e. belief whether people approve or disapprove the behaviour)and perceived behavioural control (i.e. individual's perception of the ease or difficulty of performing the behaviour) [3]. Researchers employ stage-based interventions such as education (i.e. providing information), persuasion (e.g. use of emotions), modelling and incentives to induce behavioural changes [87, 201].

However, such reflective behaviour change approaches require individuals to have intention and motivation to change behaviours, which is suitable for certain contexts (e.g. health) and specific behaviours (e.g. exercise, smoking cessation). In addition, recent reviews showed limited evidence on the effectiveness of stage-based interventions (Based on TTM and TPB)(e.g. [46, 259]). On the other hand, automatic approaches utilise the environment that the behaviour occurs in rather than require an internal motivation, which can trigger automatic responses of System 1 (and sometimes System 2) and result in behavioural changes.

2.3.3 Automatic Behaviour Change Approaches

Automatic approaches utilise the unconscious mind (System 1) to induce behavioural changes. One of these approaches is subliminal priming which triggers automatic processes by presenting stimuli below the threshold of conscious perception, which in turn activate certain affective or behavioural responses [25, 84, 218]. Nudge Theory [297] is another approach that is rooted in psychology and behavioural economics and is based on the idea that shaping the environment (also known as choice architecture) can influence the individual's choices and behaviours. Thaler and Sunstein [297] define nudging as *"...any aspect of the choice architecture that alters people's behaviours in a predictable way without forbidding any options or significantly changing their economic incentives (p.6)"*. Nudges mainly leverage System 1 to influence people's behaviours but can also leverage System 2 when dealing with reflective choices (e.g. "look right" sign painted on the streets of London) [124]. Below, I discuss these approaches in more depth.

2.3.3.1 Subliminal Priming

Priming occurs in a non-conscious form of the human memory (i.e., implicit memory) and is observed when previous experiences influence current behaviour or thought [262, 302]. There are two techniques to deliver priming; conscious or subliminal. Conscious priming, also known as "supraliminal priming", occurs above the threshold of conscious perception in which the individual is aware of the stimulus but not its purpose [25]. On the other hand, subliminal priming involves the presentation of a stimulus below the threshold of conscious perception in which the individual is not aware of both the stimulus and its purpose [25, 84]. A subliminal stimulus is a sensory stimulus that can have an impact on the brain only when presented below a person's conscious perception [93, 171]. Presenting subliminal stimuli involves very short presentation durations as well as a masking technique to ensure that that visual buffer has been overwritten [25].

Behavioural and neuroimaging studies have reported the influence of subliminal stimuli on performance at various levels; motor, visual, lexical, semantic and affective [80, 116, 158, 171, 239]. For instance, researchers showed that subliminally presented pictures [22], arrows [91], shapes [167], words [116] and numbers [80] can bias response decisions. In addition, cognitive neuroscientists showed brain activations in response to subliminal stimuli using techniques such as functional Magnetic Response Imaging (fMRI) and Event-Related Potentials (ERPs) [171]. fMRI and ERP studies showed evidence of subliminal perception at motor, emotional and semantic levels [80, 91, 208, 314]. Greenwald et al. [116] used fMRI and ERP to study the spatial and temporal properties of motor priming. Their fMRI results showed an activation in the motor cortex. ERP results also exhibited an activation after presenting the subliminal stimulus. These techniques show evidence that the brain is capable of processing unconsciously perceived stimuli.

2.3.3.2 Nudging

When faced with a difficult problem that requires a quick answer, System 1 employs heuristics, or rules of thumb [153]. *Heuristics* are mental shortcuts that allow people to produce judgements and make decisions without having to search and review all the relevant information [305]. For example, people tend to make decisions or evaluate a specific topic (e.g. car theft is more common in a specific area) based on immediate information that is readily available to them (e.g. seeing news about car thefts), which is known as availability heuristic [153, 305]. Although heuristics can offer quick and adequate solutions to problems, the reliance on them can make us more susceptible to *cognitive biases*[229, 305]. Cognitive biases are deviation from the rational thinking which results in poor decisions [229]. An example of such biases is the status-quo bias, which is described as people's tendency to *doing nothing or maintaining one's current or previous decision* [260], is choosing the default option instead of considering the other options.

Cognitive biases can be utilised to design nudging mechanisms for behaviour change. The field of behavioural economics have identified a wide range of nudges that leverage these biases and induce behavioural changes. Thaler and Sunstein reported six principles or nudges in their book Nudge [297]. These include i**N**centives, **U**nderstand mappings, **D**efaults, **G**ive feedback, **E**xpect error and **S**aliency/**S**tructure complex choices. Incentives involve providing monetary, material or psychological incentives to allow good decision-making processes. Understanding mappings entails making information about various options more comprehensible by mapping to known schemes. Defaults utilise the status-quo bias and involve choosing a default option for people when choice is difficult for them. Give feedback involves providing feedback to users when they are doing well and when they are making mistakes. Expect error assumes that people make mistakes when using systems and thus one must be forgiving. Saliency/Structure complex choices involves providing structure when choice becomes more complex.

In addition to these six principles, Sunstein [289] reported a list of ten important nudges. These include the use default rules, simplification of complex programs, the use of social norms, disclosure of information (e.g. costs), the use of salient warnings or graphics, committing to specific actions to be done at specific time in the future, the use of reminders, asking people about implementation intentions and informing people about the consequences of their past choices. In the UK, the government's Nudge Unit published a report explaining a framework called MINDSPACE [87], which draws on nudge. The framework describes nine influential nudging mechanisms that aim to impact and alter behaviours. These include: Messenger, Incentives, Defaults, Salience, Priming, Affect, Commitment, and Ego. Table 2.1 explains each of these nudging mechanisms. Research has later confirmed the effectiveness of the MINDSPACE nudging mechanisms to nudge people towards certain decisions or behaviours [37, 294].

Table 2.1: MINDSPACE Framework, adapted from [87]

Mechanism	**Description**
Messenger	We are heavily influenced by who communicates information to us
Incentives	Our responses to incentives are shaped by predictable mental shortcuts such as strongly avoiding losses
Norms	We are strongly influenced by what others do
Defaults	We 'go with the flow' of pre-set options
Salience	Our attention is drawn to what is novel and seems relevant to us
Priming	Our acts are often influenced by sub-conscious cues
Affect	Our emotional associations can powerfully shape our actions
Commitments	We seek to be consistent with our public promises, and reciprocate acts
Ego	We act in ways that make us feel better about ourselves

The aforementioned nudges mainly utilise System 1 to influence behaviours. However, nudges can also leverage System 2 when aiming to influence reflective choices. For example, Hansen et al. [124] presented a framework for nudges and differentiated between different types of nudges based on two dimensions: mode of thinking and transparency. Mode of thinking divides nudges into *automatic* nudges and *reflective* nudges. Automatic nudges aim to influence behaviours that are maintained by the automatic thinking and that do not involve reflective thinking (i.e. reflection, judgement and choice). Reflective nudges aim to influence behaviours of the reflective thinking (e.g. choices) by influencing the automatic thinking. Nudges are further divided based on transparency. Transparent nudges are nudges where the intention behind it and the means by which behavioural change is tracked are transparent to the individual being nudged whereas non-transparent nudges are nudges where the intention and means are not transparent to the individual. An example of transparent automatic nudge is using fake speed bumps to control speed and an example of non-transparent automatic nudge is organ donation opt-in/opt-out. "Look Right" sign painted on London streets is an example of transparent reflective nudges, whereas framing of medical treatments risks to influence decision-making is an example of non-transparent reflective nudges [124].

2.3.4 Summary

In this section, I discussed how behavioural economics use economics concepts along with behavioural science in order to understand how people make their decisions. I discussed the dual-process theories of decision-making and the two modes of information processing: System 1 and System 2. Then, I reviewed the behaviour change approaches that utilise these these systems including reflective and automatic behaviour change approaches. Next, I focused on reviewing automatic approaches in more depth, since it is the focus in this thesis. I discussed approaches such as subliminal priming and nudging and how they have been used to influence behaviours and decisions. However, our understanding of how these automatic approaches can utilise the different environmental cues to affect spatial behaviour, particularly navigational decision-making, remains limited.

2.4 Ambient Technologies

In the computer for the 21st century [328], Mark Weiser introduced his vision of *"Ubiquitous Computing"*, which highlighted the integration of computers in our everyday life by pushing them into the background (require little attention) and making them invisible and ubiquitous:

"The most profound technologies are those that disappear. They weave themselves into the fabric of everyday life until they are indistinguishable from it." (Weiser, 1991)

Since this vision, computers have gone far beyond the traditional PCs and witnessed significant software and hardware developments. For example, technologies such as ambient displays which Wisneski [337] described as *" a new approach to interfacing people with online digital information"*(Wisneski et al., 1998) have taken various forms and shapes to enable their integration with the environment. Instead of presenting information on a screen, with ambient technologies *"information is moved off the screen into the physical environment, manifesting itself as subtle changes in form, movement, sound, color, smell, temperature, or light"* (Wisneski et al.,

Figure 2.4: The Dangling String installation desgined by Natalie Jeremijenko [329, 330]

1998) [337]. Hence, augmenting architectural spaces and conveying information unobtrusively to users without requiring their focused attention.

2.4.1 Passive and Active Ambient Displays

One of the early examples of ambient displays is the "Dangling String" installation designed by Natalie Jeremijenko [329, 330], which was an 8 feet piece of plastic spaghetti hung from the ceiling that whirled depending on the amount of network traffic (See Figure 2.4). Since then, numerous examples of public ambient displays have been developed to communicate a variety of information; including network usage [329], e-mail traffic [142, 244], weather [132], stock [117], currency [309], public transportation information [187, 273], physical activity [251], time [128, 221] and presence of people [75, 128]. Thus, a wide range of ambient displays designs have been explored to communicate these information unobtrusively, ranging from physical installations such as kinetic sculptures [65, 142, 187, 251, 257, 329], water-based installations [75, 128, 309] and light-based installations [212, 221, 251] to screen-based displays (i.e. LCDs) [244, 251] and projections [132, 272] (See Figure 2.5). This body of research has focused on using ambient displays as passive gateways into the digital world [136] that communicate dynamic information to users while offering limited interaction with the displays. In fact, Mankoff et al. [187] discussed that ambient displays and traditional displays differ in the way users interact with the display and explained that ambient displays are perceived and not used. Since users do not interact with these ambient displays explicitly, the type of supported interaction can be characterised as an indirect interaction (i.e. mediated), in which users do not realise that their actions (e.g. human

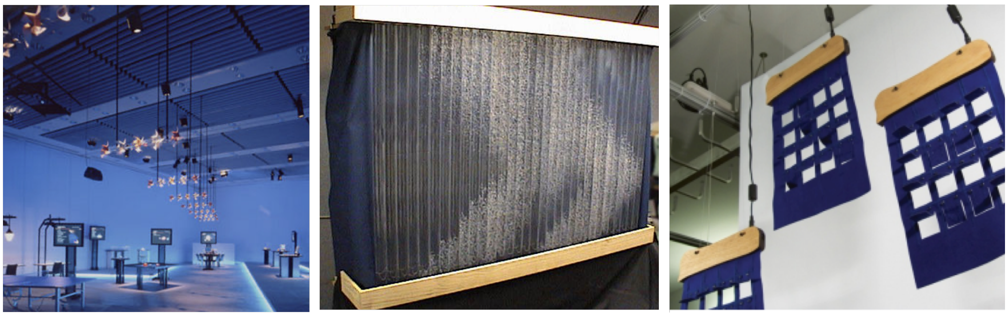


Figure 2.5: Examples of ambient displays for information communication: Pinwheels [142], The information percolator [128] and Shutters [65].

behaviour, physical activity, email and network usage) are used as input sources [243].

In addition to the indirect interaction provided by ambient displays, few early implementations of ambient displays have offered direct interaction (i.e. unmediated) with displays. In this case, displays act as an ambient as well as an interactive display. Interaction techniques employed in such displays can be implicit (e.g. using body orientation, position or proximity cues) [207, 322] or explicit (e.g. using hand gestures, touch screen input or mobile devices) [237, 322, 331]. In one of the early examples, White et al. [331] presented the interactive poetic garden, which is an interactive public ambient display, consisting of words projected on the surface of flowing water, that allows users to passively and actively interact with the floating words. Later, researchers proposed to clearly define the zones in which users can interact with ambient displays. For instance, Hello.Wall [237], which is a wall-sized ambient display that used light patterns to communicate atmospheric information, defined three zones of interaction depending on the user's distance from the wall. In the ambient zone (i.e. the user falls outside of the range the wall's sensors), the display shows general information. If the display detects a person in the notification zone, data can be sent to a handheld device and then personal or public light patterns can be shown on the wall. Users can interact and manipulate individual wall pixels when they are very close to the wall and fall in the interaction zone. Building on and extending this work [237], Vogel and Balakrishnan [322] further explored design principles and an interaction framework for interactive public ambient displays. They presented an interactive public ambient display that can transition seamlessly from distant implicit public interaction to close explicit personal interaction. Four phases of interaction were defined, which were entered and exited in a smooth way, including ambient display, implicit, subtle and personal interaction. A recent example of an interactive public ambient display explored the use of an interactive floor-projection of walking trajectories to support social awareness [207]. The display served a dual role; providing public ambient information about other inhabitants in the space (that can be easily moved to the periphery) and offering an interactive floor that supports active engagement and experimentation. Displays that support ambient and interactive experiences are built on the idea that ambient information invites users for explicit interaction with the display [137]. While these are interesting explorations of ambient technologies, their nature makes evaluating them difficult [126, 187].

2.4.2 Evaluating Ambient Technologies

Ambient technologies aim to communicate information in an unobtrusive manner. With this goal, evaluation of such technologies becomes complex and costly due to difficulties in measuring their effectiveness [187]. Although many ambient technologies have been designed and developed so far, evaluation styles have not been consistent and various styles have been used to evaluate them. Some technologies have been evaluated in laboratory (e.g. [12, 71, 222]) and it-situ (e.g. [126, 251]) settings, while others have either conducted informal evaluations (e.g. [61, 217, 322]) or have not been evaluated at all (e.g. [128, 143, 329]). Mankoff et al. [187] proposed the use of a a different, low-cost evaluation methodology, heuristic evaluation, to evaluate the effectiveness of ambient technologies.

Laboratory Evaluations mainly use specific tasks to assess the effectiveness, functionality or usability of the developed technology [126]. In such controlled studies, the researcher takes notes while observing the participant completing a given task. For example, to evaluate Waterbot [12], which is a persuasive ambient display that motivates behaviour change at the sink, researchers asked ten participants to wash their hands in a sink that had waterbot installed on it while the researcher is observing the behaviours and recording their reactions and comments. Their evaluation provided an understanding of how participants perceived Waterbot's feedback. In addition, Occhialini et al. [222] evaluated their ambient display that support time management during meetings through five experimental sessions conducted in controlled conditions. Data were collected by observing participants during these sessions and conducting post-experiment interviews. Their evaluation provided important insights about the perceived usefulness of their ambient technology. Such lab evaluations offer more control over confounding variables and can provide crucial insights into the functionality or usability of an ambient technology, however, it is unclear if users would use the technology in the same way when it is deployed in its natural setting. Also, the understanding of their long-term impact on behaviour remains limited with lab evaluations.

In-Situ Evaluations are conducted over a period of time to provide a better understanding of the developed ambient technology in its natural setting. Data collection usually involves conducting multiple interviews with users (pre and post deployment), questionnaires and observation that focus on evaluating the enjoyment while using the technology as well as long-term effects on users. For instance, Rogers et al. [251] evaluated three ambient displays: *The Clouds*, *Follow the Lights* and *The History*, which aim at subtly changing how people move through a building (i.e. using the stairs or the elevator), in an eight-week in-situ study. Data collected included sensors logs, observations, interviews and an online survey. The evaluation resulted in valuable insights into the long-term impact of the ambient displays on people's behaviour within the building. In addition, CareNet Display [70], which is an ambient display that helps care network members in tracking an elder's care-related activities, was evaluated in a three-week in-situ evaluation. Interviews and questionnaires were used mainly to collect data from care network members (participants) and elders. The evaluation provided useful insights into the effectiveness of CareNet Display in supporting carer network members in tracking elders' daily life. Although in-situ evaluations provide better understanding of the long-term impact of ambient technologies on people, they can raise some issues [126]. For example, Hazlewood et al. [126] reported that observing and interviewing people during in-situ evaluations interfered with people and impacted the awareness of the displays. Also, with in-situ evaluations inconsistencies can occur when comparing self-report with logged data.

2.4.3 Summary

In this section, I introduced Weiser's vision of Ubiquitous Computing and presented ambient technologies which were developed based on this vision. I reviewed prior examples of ambient technologies and discussed how such technologies have developed from communicating information indirectly to offering direct interaction capabilities. Then, I discussed the challenges in evaluating ambient technologies and the different evaluation styles including, laboratory and In-situ evaluations.

2.5 Persuasive Technologies

An interactive computer system designed to change individuals' behaviours is known as a *"Persuasive Technology"* [100, 101]. Persuasive technologies have been designed mainly to promote health and encourage sustainable behaviours [2]. In a systematic review of persuasive technologies, Adams et al. [2] distinguished between two types of persuasive technologies: reflective (i.e. act upon System 2 process) and automatic (i.e. act upon System 1 processes). The results of their systematic review showed that most of the current persuasive technologies were designed to act on System 2 processes and only 11 out 176 papers reviewed were designed to utilise System 1 processes. Research exploring both types of persuasive technologies have used platforms such as mobile devices, desktop applications and ambient displays.

Research into ambient technologies has exhibited many developments over the last decade. Rather than focusing on communicating information unobtrusively, ambient technologies have extended their potential and have become a tool to support behaviour change. Various behaviour change mechanisms have been used in persuasive ambient technologies, including providing feedback and raising awareness, reminding users of changing behaviours and using different nudging mechanisms such as salience and social influence. In this section, I discuss reflective and automatic persuasive technologies and review prior work that use various technological platforms to deliver behaviour change interventions, focusing more on ambient technologies.

2.5.1 Reflective Persuasive Technologies

Reflective persuasive technologies depend on the user's internal motivation and ability to achieve behavioural changes [2]. These technologies utilise current behaviour change theories and models such as Transtheoretical model [112] (e.g. [127]) and the Goal Setting Theory [179] (e.g. [68]). Reflective persuasive technologies have been mainly used to promote healthy behaviours (e.g. [68, 145]) and encourage sustainable behaviours(e.g. [127]). Various technological platforms were used to deliver such behaviour change interventions, including mobile and handheld devices, desktop applications, physical objects, wearable devices and ambient and public displays [225].

Prior work have used mobile devices, desktop applications and physical objects as platforms for behaviour change(e.g. [69, 178, 298]. For instance, Consolvo et al. [69] developed UbiFit Garden, which uses on-body sensing, machine learning to infer users activities and a mobile device to encourage physical activity. Based on the data collected from the sensors, the mobile display shows aesthetic representation (i.e. in the form of flowers and butterflies) of physical activities and goal attainment to motivate physical activity. Their findings showed that the system was motivating and well-received. In another study, an interactive computer game was developed to encourage physical activity [178]. Fish'n'Steps [178] motivates users to take more steps everyday by linking daily step count of users to the growth and activity of a virtual fish in a virtual tank. Their evaluation showed that more than half of participants either changed their attitude towards physical activity or increased their daily steps. In addition, researchers have utilised physical objects to encourage behavioural changes. For instance, Thieme et al. [298] designed BinCam which is a social persuasive system to induce behavioural changes in food waste habits. The system consists of a bin that logs thrown away items (by capturing images using a mobile phone installed on the bin's lid) and uploads images on Facebook for other users to view. Their results revealed an improvement in users' awareness of their waste and a motivation to improve their food waste habits.

Reflective persuasive technologies have leveraged ambient displays to deliver behaviour change interventions, targeting primarily health-related and sustainability behaviours (e.g. [103, 145, 174]). For example, Jafarinaimi et al. [145] designed an ambient display to discourage sedentary behaviour. The ambient display is in the form of a sculpture that has lifelike qualities. By changing its pose, the sculpture reminds the user that she needs to take a break as she has been sitting for a long time. Their initial evaluation showed that such an ambient display can promising in inducing behavioural changes. Additional persuasive ambient technologies that encourage physical activity include the Health Bar [189] and MoveLamp [103], which uses light feedback to remind users to take breaks, and the Break-Time Barometer [165], which encourages taking breaks at work by promoting social awareness of the occurrences of breaks. Furthermore, persuasive ambient technologies have been used to promote sustainable behaviours.

For instance, Kuznetsov et al. [174] presented different ambient display designs for motivating water conservation. These included numeric and an abstract visualisation (i.e. light) of water usage data. Their evaluation showed that the light ambient display reduced water usage by around 2 gallons per shower in all households, whereas the numeric display was effective in reducing usage in only half of the participants. In addition, Gustafsson et al. [121] designed the Power-Aware Cord, which is an ambient display that aims to raise awareness regarding power consumption and induce behavioural changes. The cord shows the current use of electricity through the use of glowing light. Their initial evaluation reported positive responses from participants who found the Power-Aware Cord was intuitive.

While reflective persuasive technologies can be effective in inducing behavioural changes in various contexts, there are limitations associated with using them such as the requirement of having motivation and ability (i.e. requires conscious awareness). However, in certain situations, there is a need to influence choices and behaviours without requiring conscious awareness.

2.5.2 Automatic Persuasive Technologies

Automatic persuasive technologies rely strongly on System 1's processes to achieve behavioural changes [2]. Adams et al. [2] used the term Mindless Computing technology to refer to *"a mobile or ubiquitous, persuasive technology designed to subtly influence the behavior of the user without requiring their conscious awareness"*. In their work, they discuss that automatic responses of System 1 can be triggered through subliminal priming or nudging mechanisms. So far, many technologies have been designed using these mechanisms and have shown promising results. Below, I discuss research works that utilise these automatic mechanisms to influence behaviours.

2.5.2.1 Technologies Using Subliminal Priming as a Behaviour Change Mechanism

Subliminal priming in HCI have been found to be useful in enhancing the interaction efficiency between humans and computers as it transfers information without causing additional workload on the sensory channels [218, 246]. Previous work have explored its use in various applications such as enhancing learning [60], providing assistance [83], improving experiences in virtual environments [11, 54] and changing behaviours [52, 123, 236, 247].

Subliminal priming have been explored as a way to change health-related behaviours [52, 236] as well as driving behaviours [246, 247]. For example, Pinder et al. [236] explored the feasibility of using subliminal priming on smartphones as a non-conscious behaviour change technique. They investigated the impact of stimulus types (polygons, faces and text) on liking judgements. Their results indicated that showing a subliminal text stimulus once decreases the likelihood of it being preferred compared to the control and polygon conditions. However, other types and conditions (i.e., photos and repetitions) did not increase the preference likelihood. In another behaviour change application, Caraban et al. [52] designed a subliminal priming plug-in for Google Chrome browsers. The subliminal stimuli were presented as a slight emphasis on words (behavioural concepts promoting healthier lifestyle) which were presented at different locations within the webpage. Their study showed that subliminal stimuli were selected significantly more than the other conditions. Also, Research has explored the feasibility of influencing choices using subliminal stimuli. For instance, Cetnarski et al. [54] used a mixed-reality system to study the impact of subliminal stimuli on navigation decisions in a virtual maze. Their findings showed that navigation decisions were influenced by the graphical subliminal stimuli. In addition, Aranyi et al. [11] investigated whether subliminal stimuli (3D food items) could bias selection behaviour in a food selection task. Their results demonstrated a significant overall priming effect in the selection task, but the magnitude was not large enough for practical interface applications.

Thus far, research that employs subliminal priming as a mechanism to influence behaviours and choices has focused on delivering it through web interfaces and mobile apps. However, it remains unclear whether and how subliminal priming can be used in ambient technologies. Therefore, there is a need to investigate whether subliminal stimuli can be effective at influencing decisions when presented in the periphery in order to embed them in ambient technologies.

2.5.2.2 Technologies Using Nudging as a Behaviour Change Mechanism

Since the introduction of the concept of nudging [297], researchers in the field of HCI have developed systems that aim to nudge and influence choices and behaviours. These systems employed various nudging mechanisms such as provision of information, reminders, salience and social norms (e.g. [155, 251, 326]. Caraban et al. [51] conducted a review of nudging in HCI and reported 23 nudging mechanisms, arranged in 6 main categories, and utilising 15 distinct cognitive biases and heuristics. Nudging in HCI have been applied in multiple contexts, including health, sustainability, security and privacy and various technological platforms were used to deliver it, including web applications, mobile applications, physical objects, public and ambient displays and smartwatch applications [51].

The majority of the technology-mediated nudges were delivered through web applications [52]. Such web applications were, for instance, used to encourage healthier food choices while shopping online [104] and improve privacy practices on social media [326]. For example, Forwood et al. [104] designed an online supermarket that offers shoppers healthier swaps of the chosen food items at the the point of selection or at checkout. This nudging intervention, however, did not significantly affect food choices as findings showed that shoppers accepted only a mean of 4 swaps out of the 12 food items purchased. In another web application, Wang et al. [326] designed a web plug-in for Facebook that nudges users to consider their online disclosures. They evaluated two nudges: a timer nudge, which encourages users to stop and reflect before posting, and an audience nudge, which reminds users about the audience of posts. Their findings showed that the audience nudge can be effective in avoiding unintended disclosures, whereas the timer nudges was found to be useful and at the same time annoying. Mobile applications have also been used to nudge users to review their information disclosure. For instance, Almuhimedi et al. [6] designed nudges to raise

Figure 2.6: Three ambient displays designed to nudge people to take the stairs: Follow-the-Lights, the Clouds and the History [251].

the awareness of users of the data collected by their apps (e.g. location). Such nudges were found to be highly effective, with 95% of participants reevaluating the permissions given to these apps.

A recent review of technology-mediated nudges [51] reported only little research that use ambient technology as a platform for altering behaviours using nudging. Such ambient technologies have examined various nudging mechanisms to nudge people at the point of decision-making. For example, Kalnikaite et al. [155, 156] designed an ambient display, "The Lambent Shopping Handle", to support decision-making and nudge supermarket shoppers into making better product choices. The lambent shopping handle is a device that attaches to a shopping trolley and provides personal ambient feedback about scanned products. The handle design employs a combination of two nudging mechanisms: *salience of information* and *social norms*. Nudging using both mechanisms resulted in a significant influence on people's products selections. In another study, Rogers et al. [251] designed three inter-linked ambient displays: Follow-the-Lights, the Clouds and the History, to nudge people to take the stairs instead of the elevator, as shown in Figure 2.6. The nudging technique behind the Clouds and the History was to provide feedback regarding the stairs/elevator usage and allow people to reflect when encountering the decision point whereas Follow-the-Light nudges people through interactive and alluring design that distracts people from the elevator and allow them to take actions. While their qualitative findings demonstrated that people were not aware of any behavioural changes that occurred as a result of noticing the displays, the logged data showed a statistically significant change in stair/elevator usage after deployment of the installation. In addition, Moere et al. [206] designed a wall-sized ambient display that shows a collection of flowers representing the country of origin of products customers have bought at a local coffee shop to influence and nudge their choices. By raising the awareness of the amount of foreign products bought, customers were expected to buy more local products. However, the impact of this ambient display on purchase decisions was low because of difficulties in interpreting the meaning of the display.

However, the aforementioned persuasive ambient technologies focused on addressing a limited set of behaviours such as health-related and shopping behaviours, and only few studies have explored using ambient technologies to nudge and influence navigational decision-making. Research has shown that ambient technologies can be designed in order to nudge and influence navigation decisions. For example, Varoudis et al. [312, 313] showed that an ambient display that extends the visual depth and shows a projection of a nearby space has the potential to nudge people and influence their path choice behaviour. They demonstrated that placing such an ambient display on the right or the left side of a corridor causes significant changes in the choice of the path towards the side at which the display is located. However, while this work proposed that such ambient displays can be used to nudge and direct people's movement to remote spaces, their work focused on examining LCD ambient displays (and did not examine the widely used non-pixel ambient displays), which have been found to suffer from display blindness [215, 251].

In addition, as part of their *ambient influence* approach that examined three types of ambient displays to nudge people to change their behaviour, Rogers et al. [251] designed an ambient display called "Follow-the-Lights" to influence navigation decisions and nudge people to take the path leading to the stairwell through an aesthetically pleasing, interactive floor-embedded LED lights that creates a flowing pattern when approached by people. While this work showed how effective a distributed ambient display at influencing behaviour, it is not clear which one of the displays was more influential and therefore, there is no clear evidence that nudging using "Follow-the-Lights" display was effective at influencing path choices.

In another work, Boehm et al. [38, 39] proposed embedding persuasive ambient technologies in existing infrastructure to solve problems pedestrian's face in public transport facilities such as collisions at blind corners. They presented ambient solutions that act as psychological guiding measures to nudge pedestrian's movement patterns. One example of such guiding measures was designing anamorphic graphics, which are flat, motionless graphics that transform into a 3D shape when viewed from a certain viewing angle, and placing them at an intersection corner. Their findings showed that a 3D illusion of a physical object had a significant effect on movement behaviours. While this work showed how an ambient, unobtrusive nudging interventions can be designed to influence movement patterns, their intervention focused on shifting people away from a wall and not on influencing their path choice behaviour. In addition, although the authors presented other solutions to guide movement patterns (e.g. Digital Hagioscope, Parallax Motion Display), their work focused on studying anamorhpic graphics and hence it is not clear whether the other proposed solutions are effective at influencing movement patterns.

Although the studies described above acknowledge the potential of using ambient displays to influence navigation decisions, none of them investigate systematically how nudging mechanisms can be incorporated in the design of ambient displays to influence navigational decision-making. Hence, we still lack a systematic investigation of how ambient technologies can be designed to nudge and influence navigation decisions to support users while exploring unfamiliar spaces.

2.5.3 Summary

In this section, I presented persuasive ambient technologies and discussed how such technologies are not limited to communicating information but can also support behaviour change. I discussed two types of persuasive technologies; reflective and automatic technologies. Because of the focus of this thesis, I reviewed in more depth the automatic persuasive technologies. I particularly discussed prior work that use subliminal priming and nudging as a behaviour change mechanisms. While there are several persuasive technologies that were developed using these behaviour change mechanisms, there is a lack in research works examining how persuasive ambient technologies can be designed to influence navigation decisions using these mechanisms. Therefore, our understanding of whether and how such technologies can be designed and used to support navigational decision-making remains limited.

2.6 Techniques to Attract and Guide Passers-by Towards Public Displays

A wide range of interactive public displays have been deployed in public settings, with various methods employed to study and evaluate them in such spaces [8, 334]. While such displays mainly aim to support or entertain users, many of them get unnoticed and ignored (i.e. display and interaction blindness) [215, 223]. Research has explored many ways to attract the attention of passers-by, influence their spatial behaviour and direct them towards the public display for further interaction, including physical and social cues (e.g. [109, 173]). Physical cues include using cues such as animations, physical objects or additional displays, whereas social cues involve using cues such as other people or the traces they leave behind. In this section, I discuss these cues types and how they are used to influence spatial behaviour around public displays.

2.6.1 Physical Cues Affecting Spatial Behaviour Around Public Displays

To affect the passer-by's spatial behaviour around public displays and attract interactions, researchers have examined showing different types of visual stimuli (e.g. colour [7, 173] and animation (motion) [7, 109, 173]), use physical objects [152] as well as employing a combination of non-flat displays [295]. In addition, Vogel et al. [322] employed proxemics and proposed a phased method, which changes the presented information as passers-by come closer to the display, to impact their spatial behaviour around the display and invite interactions. While the aforementioned approaches tend to use the public display itself to attract attention, other approaches introduce a secondary interactive public display to direct movement of passers-by to the primary public display. For instance, Vermeulen et al. [315] proposed the use of interactive floor displays as a secondary display to guide users to primary displays and presented a design space for floor visualisation strategies.

2.6.2 Social Cues Affecting Spatial Behaviour Around Public Displays

While the aforementioned physical cues are considered a powerful tool to attract attention and affect passer-by's spatial behaviour around the display, social cues are also considered as influential. One of the most commonly reported and strongest effects in public displays literature is the honeypot effect [47] which describes the social influence of people being drawn to the public display by other people already interacting with it. Several studies have shown that such an effect is powerful in attracting attention of passers-by and influencing their behaviour around the display [47, 188, 200, 214, 231]. In addition to the influence of the actual presence of other people on the passer-by's spatial behaviour around public displays, leaving traces of people's previous presence can also draw attention to the public display and affect behaviours. Monastero et al. [207] demonstrated how projecting users' walking trajectories can support social awareness and showed how such display can affect people's spatial behaviours within and around the interactive floor.

2.6.3 Summary

In this section, I discussed the techniques that researchers have used with public displays in order to attract and guide passers-by towards them including, physical cues and social cues. I reviewed examples of physical cues, which include using visual stimuli such as colour, physical objects and using a collection of non-flat displays. I also discussed different types of social cues including, the presence of actual people (creating the honeypot effect) and the presence of their traces.

2.7 Guided Walking using Sensory Illusions

Systems that present sensory illusions have been developed to implicitly direct walking direction. For example, research in the field of computer vision used visual (e.g. [106, 176]) and acoustic(e.g. [105]) stimuli to affect walking direction. Various approaches have been proposed to induce change in movement patterns including, environmental (i.e. using large displays) and wearable (i.e. using wearable devices such as head-mounted displays). Here, I discuss these research projects and explain their limitation.

Furukawa et al. [106] proposed a novel method for influencing walking direction using "Vection Field", which presents optical flow on the floor. The optical floor is displayed using a lenticular lens, which generates dynamic visual effect without needing an electrical power supply. The evaluation results showed that the Vection Field approach produces significant directional shifts in walking patterns and hence can be used as a type of intuitive walking guidance. Rather than using a lenticular lens, which suffers from limited viewing angle, Sakamoto et al. [258] proposed the parallax barrier method, which makes the viewing angle wide and reverses the direction of visual motion depending on the viewpoint. Their findings demonstrated that affecting walking direction, using a visual stimulus of black and white lines moving in one direction and presented on the floor, is possible. Similarly, Leonards et al. [176] examined how floor patterns (i.e. paving slabs) influence walking direction. Their study investigated the participants' ability to walk straight in 16 different pattern orientations. Findings showed that the oblique pattern orientation of the floor patterns has substantially affected participants' walking direction and veered them away from walking straight ahead. The aforementioned research works employ floor projections to display patterns on the floor. In contrast, Ishii et al. [141] presented a wearable approach to manipulate walking direction of users unconsciously using a head-mounted display. The system processes images collected from a stereo camera and provides real-time feedback to users. In their work, they particularly use two techniques to affect walking direction: moving stripe pattern and changing focal region. Findings indicated that both techniques were successful. However, the changing focal region technique was more effective and resulted in a change in users' walking direction by about 200mm/m on average.

In addition to using systems with visual stimuli to induce behavioural changes in peoples' walking directions, research has showed that systems that present environmental acoustics can also affect movement directions. For instance, Fujinawa et al. [105] presented a method to implicitly induce changes in peoples' walking directions by dividing a space using acoustics field generation methods into a comfortable zone and uncomfortable zone. These zones are created based on the environmental sound used, which in turn affects peoples' rating of the pleasantness of the space. By evaluating two types of environmental sounds: environmental noise (unpleasant sound) and background music (pleasant sound), their findings showed that participants stayed longer in the low sound pressure zone with the unpleasant sound. However, the impact of these environmental acoustics on walking direction was not significant.

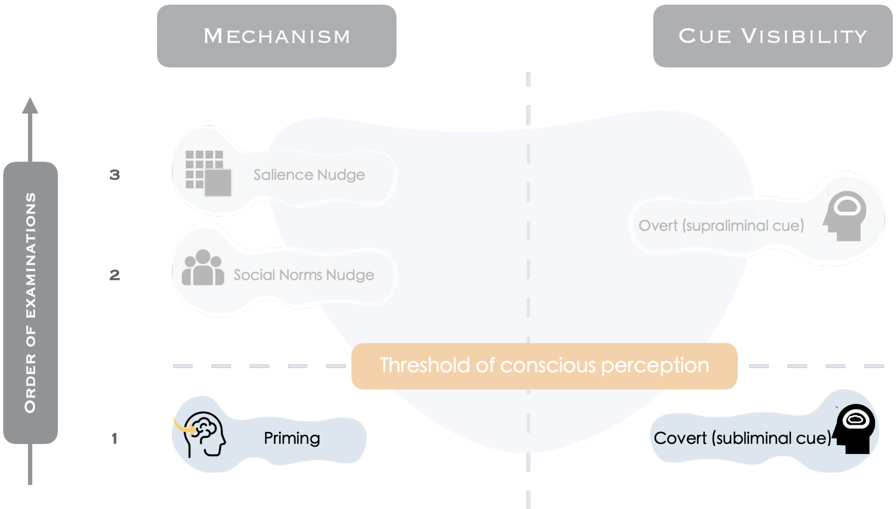
2.7.1 Summary

In this section, I discussed research works from the computer vision field that aim to guide walking direction implicitly using sensory illusions. I reviewed prior work that used visual as well as auditory stimuli to influence walking direction. While the previously discussed research works present promising approaches into influencing walking patterns unconsciously, they are limited to generating slight shifts in walking direction and not influencing navigational choice. This thesis, however, aims to examine how ambient technologies can be leveraged to implicitly influence navigational decision-making.

2.8 Conclusion

In this chapter, I presented literature from diverse disciplines in order to provide theoretical grounding for this thesis, which serves as a foundation for understanding the following chapters. I provided an overview of the main theoretical models used in environmental psychology, which helps in understanding the human-environment relationship, and discussed the different environmental cues that affect path choice behaviour. Then, I reviewed the dual-process theories of decision-making used in behavioural economics and the various approaches for behaviour change that utilise the two modes of information processing. Next, I discussed relevant existing technologies including, ambient technologies and persuasive technologies. In the next chapter, I start my empirical examinations with the lowest cue level, i.e. subliminal cues and examine them with the priming mechanism.

Chapter 3
Priming Mechanism with Subliminal Cues



CHAPTER 3

Exploring Subliminal Cues - A Preliminary Study

THIS CHAPTER:

- Presents a preliminary study that investigates the degree to which subliminal stimuli are effective at influencing decisions when presented in the periphery of the vision field.
- Describes how three types of subliminal stimulus (images, shapes, words) presented at thirteen visual angles and tested using two presentation durations (33ms, 66ms) influence selection performance.
- Concludes that subliminal cues are not suitable for use in ambient technologies due to the inconsistencies in the influence of subliminal cues on decisions.

I have published the study presented in this chapter in [J.1].

3.1 Introduction

In HCI, subliminal priming have been used to enhance and enrich the interaction efficiency between humans and computers [218, 246]. Prior work have used subliminal cues in various application domains such behaviour change [52, 123, 236, 247], education [60], assistance [83] and gaming [11, 54]. These previous efforts have tested this concept by presenting the subliminal cue at the centre of the screen while the user is asked to focus on that central location during a given task. Furthermore, previous work has focused on examining specific types of subliminal cues including, textual [52, 83] and graphical [11, 54, 60, 247] that are presented at specific presentation durations. However, the extent to which subliminal priming mechanism is effective at influencing decisions in different conditions remains limited. In particular, it is unclear whether subliminal cues could affect decisions when presented outside of the central area and in the periphery of the visual field. Also, it remains unclear which stimulus type and presentation duration are more effective at influencing decisions when presented in peripheral areas. This understanding of how subliminal stimuli perform in the periphery is essential for ambient technologies (which utilise the periphery of the vision field), where subliminal cues can be employed to influence decisions unobtrusively without impacting primary tasks.

In this chapter, I present a preliminary study that compares different types of subliminal visual stimuli and presentation durations and examines them when presented in the periphery of the vision field. In particular, the study explores three types of visual stimuli (images, geometric shapes and words), presented at thirteen visual angles and tested using two presentation duration conditions (33 ms and 66 ms).

3.2 Background

3.2.1 Human Field of View

The human field of view (FOV) is a measure of the angular area that can be viewed instantaneously [43]. It covers approximately 200°-220° horizontally and 135° vertically with 60° upwards and 75° downwards. The foveal, parafoveal and peripheral visual areas work together to construct our field of view, as shown in Figure 3.1. The fovea is the central area of the retina and covers nearly three degrees of the visual field. The parafovea is the area that surrounds the fovea, and it extends to five degrees from the eye centre (i.e., ten degrees across) [287]. The peripheral vision is the area that surrounds the central vision. It is divided into three areas: near peripheral vision which spans from ± 5° to ± 30°, mid-peripheral vision which covers the area from ± 30° to ± 60°, and far-peripheral vision which covers areas above ± 60° [270, 338]. Foveal, parafoveal, near-peripheral and mid-peripheral vision areas can be seen by both eyes (i.e., binocular visual field). Far peripheral vision can only be seen with the left or right eye (i.e., monocular visual field) [254].

3.2.2 Subliminal Priming

A subliminal cue is a sensory stimulus that can influence decisions and behaviours when presented below the threshold of conscious perception [93, 171]. Subliminal stimulus presentation involves a brief presentation duration and a masking technique to overwrite the individual's visual buffer [25]. A commonly used experimental paradigm to assess priming consists of two stages. The first stage is the exposure stage, which involves presenting the stimuli. Followed by the test stage, which asks subjects to identify stimulus after a brief display, complete a frag-

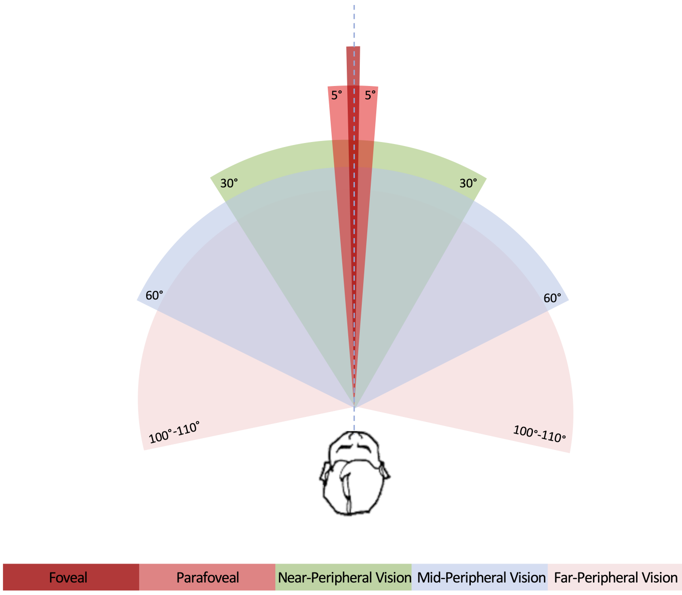


Figure 3.1: Areas of the human visual field

mented form of a word or picture or select a preferred stimulus [242, 263]. The priming effect is indicated by a facilitation or an enhanced performance in the previously exposed stimuli relative to new stimuli [262]. For example, in visual word priming tasks such as stem completion, the priming effect is observed when the stem (e.g., for__) is completed with a previously exposed stimuli (e.g., forest) [263]. In many other priming tasks, the priming effect occurs when the subliminal stimulus affects the accuracy or speed of the response [116].

Several behavioural studies have demonstrated the influence of different types of subliminal stimuli on behaviour/decisions [22, 91, 116, 167, 314]. For instance, researchers showed that subliminally presented pictures [22], arrows [91] and shapes [167] can bias response decisions. The influence of semantic priming was also explored using words and numbers. For example, Greenwald et al. [116] investigated semantic priming using a semantic categorisation task that involves words, and found that subliminal words were able to impact the judged meaning of subsequent words. Additionally, Dehaene et al. [80] performed a semantic categorisation task on numbers and showed that congruent subliminal numbers can positively affect the categorisation of following numbers (i.e., shorter reaction times). However, psychology studies tend to use a different task for each stimulus type, and it is still unclear which type is more effective at influencing behaviour/decisions if the same task was used.

Behavioural studies also examined changing the location of the subliminal stimuli and whether the location shift impacts the priming effect. For example, previous studies presented subliminal stimuli at the foveal (e.g., [80, 91, 116, 264]), parafoveal (e.g., [22, 138, 264, 286]) and peripheral (e.g., [307]) vision areas. Schiaghecken et al. [264] studied both the foveal (i.e., fixation point) and parafoveal (i.e., five degrees from the central fixation) areas and found that parafoveal presentations are also able to produce positive priming effects (i.e., shorter reaction times and lower error rates in compatible trials compared to incompatible trials). In addition, in a study that examined the impact of subliminal stimuli on saccade metrics, van der Stigchel et al. [307] presented a peripheral subliminal distractor while participants are making vertical eye movements to a target that was shown above or below the fixation point. While their study showed that a peripheral subliminal distarctor influences saccade trajectories, these results are limited to a stimulus that was presented 7.6° from the fixation point at a 75 cm viewing distance. Therefore, it is unclear whether subliminal stimuli would impact responses if presented at peripheral angles that go beyond their studied visual angle and extend to ± 60° at a viewing distance of 70 cm.

3.2.3 Subliminal Priming in HCI

Several studies have used subliminal cues in user interfaces to assist and guide users in different tasks. For instance, Devaul et al. [83] presented a wearable subliminal cueing system that provides just-in-time memory support. They used a head-mounted display to show textual subliminal stimuli of names learned during a memorisation phase. Their results showed that subliminal stimuli have significantly enhanced the identification performance of names. In addition, researchers have investigated the use of subliminal priming to enhance learning [59, 60, 151]. Chalfoun et al. [60] examined the use of subliminal cues in a tutoring system. Graphical subliminal stimuli (arrows) were presented to guide the learner in a problem-solving task. Their results showed that positive subliminal stimuli have improved the learner's overall performance.

Subliminal priming have also been explored as a way to change health-related behaviours [52, 236] as well as driving behaviours [246, 247]. For example, Pinder et al. [236] explored the feasibility of using subliminal priming on smartphones as a non-conscious behaviour change technique. They investigated the impact of stimulus types (polygons, faces and text) on liking judgements. Their results indicated that showing a subliminal text stimulus once decreases the likelihood of it being preferred compared to the control and polygon conditions. However, other types and conditions (i.e., photos and repetitions) did not increase the preference likelihood. In another behaviour change application, Caraban et al. [52] designed a subliminal priming plug-in for Google Chrome browsers. The subliminal stimuli were presented as a slight emphasis on words (behavioural concepts promoting healthier lifestyle) which were presented at different locations within the webpage. Their study showed that subliminal stimuli were selected significantly more than the other conditions.

Furthermore, subliminal priming is considered promising in improving experiences and influencing choices in virtual environments. For instance, Aranyi et al. [11] investigated whether subliminal cues (i.e. 3D food items); presented at the centre of the screen, could bias selection behaviour in a food selection task. Their results demonstrated a significant overall priming effect in the selection task, but the magnitude was not large enough for practical interface applications. Also, they showed that the priming effect was significantly larger when the stimuli were presented multiple times. Cetnarski et al. [54] used a mixed-reality system to study the impact of subliminal stimuli on navigation decisions in a virtual maze. Their findings showed that navigation decisions were influenced by the graphical subliminal stimuli.

In contrast, several studies have used subliminal priming to improve interactions but were unable to find any significant differences. For example, Gonçalves et al. [113] developed a text editor to display textual subliminal and supraliminal hints to support and assist users in creative writing tasks. However, no significant differences were found between pre and post measures of experienced creativity in the subliminal condition. Also, Pfleging et al. [235] investigated the use of subliminal stimuli to enhance visual search tasks. Their study examined graphical subliminal stimuli presented at different locations in single screen with a visual field of maximum ± 20 degrees of visual angle at 70 cm viewing distance. However, their results showed that visible stimuli were effective while subliminal stimuli could not improve search performance.

While some preliminary work show priming evidence using graphical and textual stimuli, it is still unclear which type is more effective at influencing decisions. HCI subliminal priming studies conducted so far mainly present subliminal stimuli at the centre of the visual field while the user is focused on this location, which is typical in psychology studies. For instance, Pinder et al. [236] studied different types; polygons, faces and text presented at the centre of a mobile phone. Only one study conducted by Pfleging et al. [235] studied subliminal stimuli when presented at different locations within a single screen (i.e., visual field of ± 20° of visual angle). However they only used a single screen with limited numbers of visual angles, and only one type of subliminal stimulus.

3.3 Method

To address these gaps and examine the feasibility of using subliminal cues in ambient technologies, a controlled study was conducted to examine the influence of different types of subliminal stimuli (images, shapes and words) when presented across the visual field. In particular, the study is designed to answer the following research questions:

- RQ1: For each stimulus type, can the subliminal stimulus influence the selection performance when presented in peripheral vision areas?
- RQ2: Which stimulus type shows better selection performance at the peripheral angles?
- RQ3: Which presentation duration is more effective for peripheral subliminal presentations?

To cover the selected visual field areas, twenty-three locations distributed across these areas were chosen. In particular, a previous setup used for pop-out visual stimuli [122] was reproduced. Two presentation durations were tested: 1) the average duration used in the literature to display centrally located subliminal stimuli (33 ms); and 2) a longer duration (66 ms) to test peripheral locations, as the literature suggests that the para-foveal area (i.e., the area around the fixation point) requires longer durations compared to foveal presentations [25, 276]. Ethics approval was obtained from the university's ethics committee before carrying out the study.

3.3.1 Participants

Twenty-four university staff and students (12 men, 12 women, mean age = 29.5, min=19, max=40) were recruited for the experiment. The mean duration of computer use per day was 7 hours. All had normal or corrected-to-normal vision. Participants recruited included native English speakers and non-native speakers with advanced English skills. They were recruited within my institution and received a financial incentive for their participation.

3.3.2 Apparatus

The experiment was conducted using a three-monitor setup. Figure 3.2 shows the curve arrangement of the three monitors that covers 60° of the visual field. Three 23-inch LCD screens at a resolution of 5760x1080 pixels, with a physical size of 20x11inches and a refresh rate of 60 Hz was used. The monitors were connected to a single NVIDIA graphics card. The same brightness and contrast settings were applied to the three monitors. Participants were seated 70 cm from the centre of all the three monitors. This was done by manually measuring the distance from the screens then adjusting the chair accordingly. Chairs were adjusted based on the height of each participant. The chair was then fixed and participants were instructed not to move. PsychoPy [230] running on a Windows 10 PC was used to program the study.

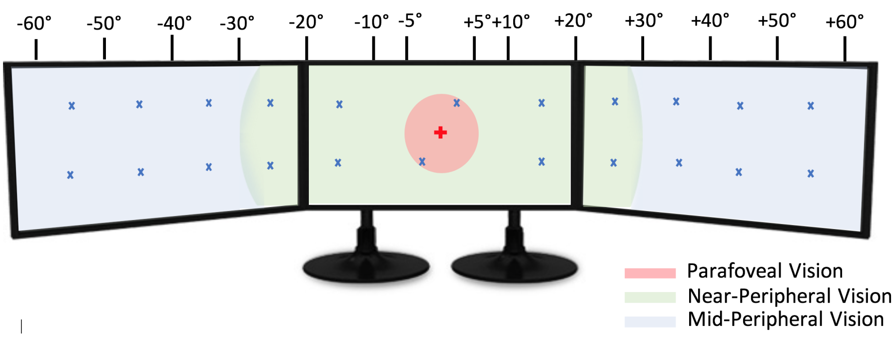


Figure 3.2: Three-monitor setup showing the selected locations in each vision area

3.3.3 Dependent Variables

The dependent variables were the success rates and reaction times. Success rates were calculated based on correct answer to the given question (i.e., whether the participant could correctly answer that the stimulus has appeared in the presentation phase). Reaction time were measured as the duration from the time the question was displayed to the time the answer was selected.

3.3.4 Independent Variables

The independent variables were stimulus type, visual angle and presentation duration. The selected settings for each variable are explained below.

3.3.4.1 Stimulus Type

Three visual stimulus types: images, geometric shapes and words were used. Figure 3.3 shows examples of the stimuli used in the study. As mentioned earlier, images and words were commonly used in the literature as subliminal stimuli. Since images and words are meaningful stimuli, they might cause a response bias. Geometric shapes, however, are abstract and meaningless stimuli and were previously used as control subliminal stimuli [236]. Therefore, in this study, the impact of these types on the given task was examined and compared. All stimuli were neutral (non-affective). Stimuli were presented in black and appeared on a white background. A list of all stimuli used in this study can be found in Appendix A

Images: Sixty-six simple black and white line drawings of office, home, clothing and nature objects were used. They were sized to 3° of visual angle at a viewing distance of 70 cm. The drawings were selected from Snodgrass et al. [277], which is a standardised set of 260 pictures suitable for experiments investigating visual perception, language and memory. This set was selected because it offers a consistent pictorial representation of common objects. Also, this set have been used extensively in priming studies (e.g., [190, 281, 323]).

Geometric shapes: Sixty-six irregular four, six, eight, twelve and sixteen-point polygons were used. They were sized to 3° of visual angle at a viewing distance of 70 cm. Polygons were adapted from Vanderplas et al. [311], which were created with the goal of being difficult to name and as nonliguistic as possible. Consequently, prior work on subliminal priming used these irregular abstract polygon set as a control stimuli when compared to stimuli that can be named such as images and words [236]. Therefore, this set was used for the abstract stimuli.

Words: Sixty-six nouns with four to six letters were used. Words were presented in lowercase letters and were sized to 3° of visual angle at 70 cm viewing distance. Words were derived from the MRC Psycholinguistic Database [335]. The average word familiarity was 545.05. Word familiarity (f) is a rating that ranges form 100 to 700, with 100 being the least familiar (i.e., meaning unknown) and 700 being the most familiar (i.e., meaning well known) [67]. Since the focus in this investigation on commonly-used visual and textual stimuli, words that are familiar and with known meaning were chosen. Words with low familiarity levels (f < 300) and words that can be recognised but the meaning might not be known (f < 400) were not included.

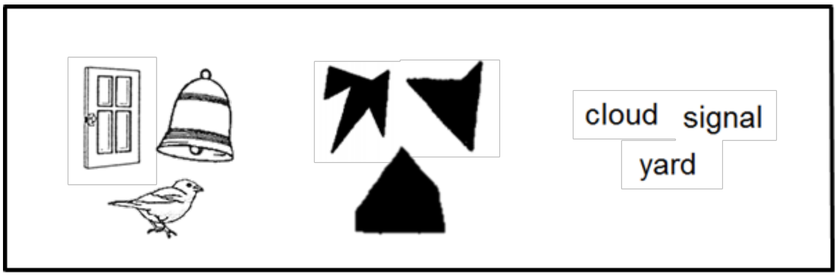


Figure 3.3: Examples of stimulus types: images, shapes and words

3.3.4.2 Visual angles

To study whether subliminal stimuli can influence selection performance when presented at peripheral vision areas, large setup was needed to explore the visual field similar to Gutwin et al. [122] who investigated the effectiveness of visual stimuli in a large display setting. Their work examined people's ability to perceive pop-out effects in the periphery. In this study, a similar apparatus setting was used to study subliminal stimuli across the visual field.

Twenty-three locations distributed across the binocular visual field were selected. The binocular visual field was divided into seven angles in both the right and the left of the centre of the visual field. To ensure the coverage of the visual field, four locations were chosen in the near-peripheral vision and six in the mid-peripheral. These locations were divided into two vertical locations (upper and lower) to reduce signal noise for each angle, as these will be collapsed into one angle in the analysis. This resulted in eight in the near-peripheral vision and twelve in the mid-peripheral vision. Also, two locations in the parafoveal vision and one location in the foveal area (See Figure 3.2). Far-peripheral vision cannot be seen with binocular vision and therefore was not included in this study.

3.3.4.3 Presentation duration

Two different presentations durations were used: 33 ms and 66 ms to test the setup. Typically, masked stimulus presented in the foveal requires an average presentation duration of 42 ms [82]. While regions that fall in the para-foveal (the small area around the centre) require longer presentation durations to be effective at influencing behaviours/decisions, as suggested in the literature [25, 276]. Thus, two durations were tested; one that is commonly used when stimuli are presented centrally, and another longer duration (double the time) to investigate whether increasing the duration would be effective in presenting subliminal stimuli in peripheral areas. The stimulus presentation was synchronized with the screen's refresh rate. Since the screens were refreshing at 60 Hz, the selected presentation durations were multiples of 16.6.

3.3.5 Experimental Design

Due to the nature of this controlled experiment which could cause participant fatigue if many factors are tested on the same participant, a mixed design was employed, with presentation duration (33 ms or 66 ms) as a between-subject factor, and stimulus types and visual angles as within-subject factors. Participants were assigned randomly to one of the two conditions: Group A, in which the stimuli presentation duration is set to 33 ms and Group B, in which the presentation duration is set to 66 ms. The three stimulus types were counter-balanced using a Latin Square and the twenty-three locations were randomised. The entire study lasted around 50 minutes per participant. Participants completed 168 trials, including 99 priming trials and 69 visibility trials. These trials are explained further below.

3.3.6 Procedure

Figure 3.4 shows the experimental procedure. First, participants received a brief introduction. Then, they were asked to sign a consent form and complete demographics questionnaire. Participants were randomly assigned to one of two experimental conditions: group A and group B explained earlier.

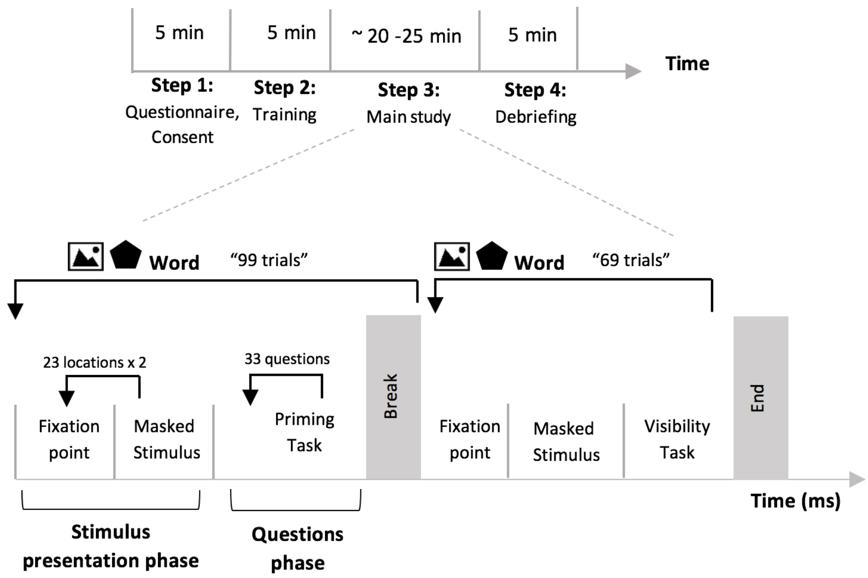


Figure 3.4: Timeline of experimental procedure

The experiment involved three successive stages: training, main study and debriefing, as shown in Figure 3.4.

1. In the training stage, participants were given practice trials to get training on how to answer the main study. The stimuli set used in training were different from the main study to avoid learning effects.

2. The main study stage was divided into two consecutive blocks: the stimuli priming block and the stimuli visibility block. The goal of the priming block was to test if the subliminal stimuli influenced task responses (i.e., whether subliminal stimuli were selected more and/or faster compared to novel stimuli, as explained below). The visibility block was added to test whether participants can detect the subliminal stimulus or not.

3. In the debriefing stage, participants were asked to report what they thought the experiment is trying to test and were asked if they were able to see any of the stimuli presented in the experiment.

3.3.6.1 Masking

To ensure that subliminal stimuli remain inaccessible to the conscious perception, very brief presentation durations must be used [82, 92]. In addition, the subliminal stimulus should be immediately masked by another stimulus [82]. In this study, a backward masking paradigm was used in which the stimulus is presented for a short time followed by a mask. Masking creates a noise to erase the stimuli image from the memory [25]. For example, with the words condition, the word "XXXXX" was used as mask. For the other conditions, a pattern mask was used, as seen in Figure 3.5. In previous work, backward masking duration ranged between 50 ms to 500 ms [11, 54, 60, 236, 255]. In this study, a masking duration of 500 ms was chosen to allow adequate time to process the subliminal stimulus before the following stimulus presentation starts.

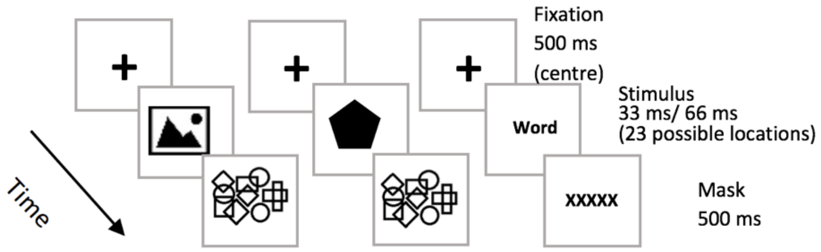


Figure 3.5: Masking patterns used in the three stimulus types

3.3.6.2 Priming block: 99 trials

The three consecutive counterbalanced sub-blocks correspond to the three stimulus types (image, geometric shape, word). For example, the image sub-block starts with the stimulus presentation phase which displays 23 image stimuli at 23 different locations randomly. Every stimulus is displayed using the following sequence: fixation point (500 ms) presented at the centre of the three screens, followed by a stimulus (33 ms or 66 ms depending on the experimental condition), and the backward mask (500 ms) both presented at one of the specified 23 locations, as shown in Figure 3.5. The stimulus presentation phase was repeated twice to increase priming effect as suggested in the literature [11, 333]. Once the stimuli presentation phase of the image type finished, the questions phase (priming task) starts by showing a list of questions on the central screen. Sub-blocks of other types would start after the completion of the first sub-block (see Figure 3.4).

A perceptual priming task similar to the task used in Aranyi et al. [11] was employed. This type of task is a selection task and is testing the visual form of the stimulus. Participants had to answer a two-alternative forced-choice question "which one of the following images/shapes/words can you identify from the previous phase?" (see Figure 3.6). One of the presented choices was a previously shown stimulus in the presentation phase and the other is a novel stimulus that has never been presented before. In addition, ten random control questions were included, in which the two choices shown were novel and were not presented in the previous presentation phase. Control questions were added to analyse the selection performance in the experimental trials versus control trials at angle level as done in the literature [83]. Participants were instructed to keep their eyes at the fixation point during the stimulus presentation phase, and to use the mouse to make selections depending on the questions that appeared on the screen. Participants were encouraged to guess if they were unsure. Each participant completed 23 experimental trials and 10 control trials for each stimulus type. The success rates and reaction times of the responses were collected. Priming was shown when better performance; higher success rates or shorter reaction times, was found [242, 263].

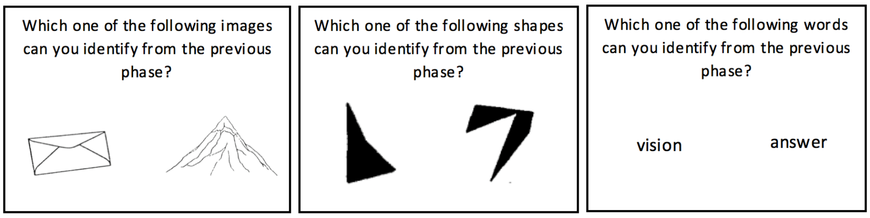


Figure 3.6: Priming task for images, shapes and words

3.3.6.3 Visibility block: 69 trials

The literature recommends conducting awareness checks after the priming task to ensure that stimuli were not visible to participants [25]. Most studies incorporate the awareness check as a second block in their experiments either as a visibility task (i.e., objective measure) [11, 54, 236] or self-reports by participants (i.e., subjective measure) [60]. In this study, an objective visibility measure was employed, similar to Aranyi et al. [11]. Participants were instructed to choose between two fixed choices based on whether they were able to see the stimulus or not. First, the central display showed the masked stimulus for 33 ms or 66 ms depending on the condition. Then, the stimulus was shown (for longer duration) with a question mark (e.g., "brain?", in the case of a word stimulus), which was either congruent (50% of the time) or incongruent with the masked stimulus. The same stimuli form was used in the masked stimuli and the visibility question (i.e., if the masked stimulus is an image, the visibility question shows an image with a question mark). Participants gave an answer by selecting between "Yes" or "No" choices. All three types were randomly presented at 23 locations in a single block, which resulted in 69 visibility trials.

3.4 Results

Before analysing the success rates and reaction times, an assessment of the stimuli visibility, which uses a sensitivity index to ensure that stimuli were subliminal, is needed.

3.4.1 Visibility Block Verification

Signal Detection Theory (SDT), which is a standard method to assess awareness, was used to measure the sensitivity index d' (d prime) for each vision area. d' is an estimate of the signal strength or a measure of the participant's sensory capabilities [220]. It is calculated by knowing the hit (H) and false alarms (F) rates for a specific area [184, 220]. Participants responses in the visibility task were used to calculate d'. The visibility task was designed to be analysed using signal detection theory, i.e., having two types of detection trials: trials were divided equally to be either congruent or incongruent with the masked stimuli. In this case, H represents the proportion of YES trials to which the subject responded $`YES' = P(`Yes'|YES)$. F is the proportion of NO trials to which the subject responded $YES = P(`YES'|NO)$.

$$d' = z(H) - z(F) \tag{3.1}$$

where H and F $\neq$ 0 or 1.

The larger the d' value, the higher the sensitivity and signal strength [282]. This means stimuli were visible and recognisable by participants. A d' of 4.65 (H = 0.99, F = 0.01) is considered an effective limit. Proportion correct of 0.90 and 0.60 corresponds to d' values of 2.5 and 0.5 respectively [184]. A d' value of zero (H = F, proportion correct = 0.50) indicates an inability to discriminate between stimuli and hence is interpreted as a lack of conscious awareness of the stimuli [11, 184]. To ensure that only stimuli that do not reach conscious awareness (subliminal) are examined, a d' cut-off value of 0 ± 0.3(error) was used. This cut-off value accounts for detection errors by limiting changes in proportion correct to $\pm$ 0.05, which ensures a maximum proportion correct of 0.55. Selecting a proportion correct of more than 0.55 would risk examining visible stimuli. Based on the cut-off value, the angles that lie in the foveal and parafoveal areas in both conditions (i.e., -5, 0, +5) were not examined because their values indicate a strong signal strength (d' > 1.5) and thus were considered visible. Several visual masking studies also found that 33 ms presentation duration was consciously perceived by the participant when they were presented at the centre of the visual field (e.g., [203, 233]). Additionally, near-peripheral area in the 66 ms condition was also eliminated from analysis (d'=0.75) and hence the angles -25, -15, 15, 25 were not studied. The remaining areas; near-peripheral and mid-peripheral areas in the 33 ms condition and mid-peripheral area in the 66 ms condition, were analysed. Figure 3.7 shows d' values for each visual field area in both presentation duration conditions (33 ms and 66 ms).

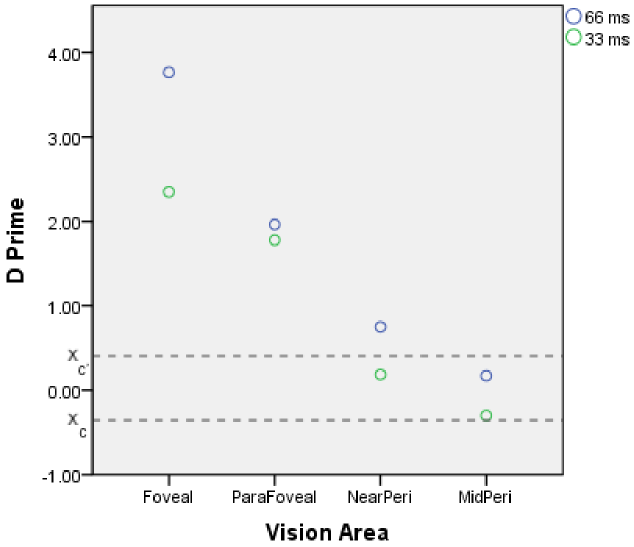


Figure 3.7: Mean d' sensitivity values in 33 ms and 66 ms duration conditions. Large d' values indicate a strong signal strength and awareness of the stimuli. X_c and X_c' represent the d' cut-off points (0±0.3(error)) of the selected subliminal stimuli

3.4.2 Priming Effect

To answer the research questions raised in this study, success rates in the within-subject factors; stimulus angle and stimulus type, were analysed using Binomial and Cochran's tests respectively. These tests were chosen as they were suitable for analysing dichotomous data. Reaction times of the stimulus angle factor were analysed using dependent t-test and reaction times of the stimulus type factor were analysed using Friedman test. The between subject factor; presentation duration, was analysed using Chi-square test for success rates and a Mann-Whitney test for reaction times. An alpha level of 0.05 was used for all statistical tests. In binomial and McNemar's (post-hoc analysis for Cochran's Q test) tests, effect size is commonly described in terms of risk ratio, odds ratio and risk difference [41]. Odds ratio of the significant results was converted to Cohen's d measure of effect size. As mentioned earlier, the angles -5, 0, 5 in both conditions and -25, -15, 15, 25 in the 66 ms condition were eliminated from this analysis due to the high value of the sensitivity index d'. In this analysis, upper and lower locations were collapsed and averaged into angles to reduce signal noise.

3.4.2.1 Within-subject analysis (stimuli angles and types)

Binomial tests were conducted to compare angle-level success rates of the stimuli types in the experimental trials with success rates in control trials. Mean success rates in control trials were at a chance level. Table 3.1 and Table 3.2 show p values of the binomial test in 33 ms and 66 ms conditions. Benjamini-Hochberg procedure [28] was applied to correct for multiple comparisons. A false discovery rate of 10% was used in all error corrections.

In the 33 ms condition, binomial tests on the word stimulus indicated that the proportion of successes at the angles -35=0.833, -25=0.792, +15=0.667,+25=0.708, +35=0.708, +55=0.708 were higher than the expected control 0.44, p(-35)=0.000 d=1, p(-25)=0.001 d=0.87, p(+15)=0.022 d=0.51, p(+25)=0.008 d=0.62, p(+35)=0.008 d=0.62, p(+55)=0.008 d=0.62 (1-sided) . No significant differences were found in success rates of the image and shape types.

In the 66 ms condition, binomial tests on the shape stimulus showed that the proportion of successes at the angles +35=0.792 and +45= 0.833 were higher than the expected control 0.57, p(+35)=0.019 d=0.59, p(+45)=0.006 d=0.74 (1-sided). A binomial test on success rates of the word stimulus indicated that the successes proportions at the angles -45=0.583, -35=0.667, +35=0.583, +45=0.625, +55=0.583 were higher than the control proportion 0.38, p(-45)=0.031 d=0.47, p(-35)=0.004 d=0.66, p(+35)=0.031 d=0.47, p(+45)=0.011 d=0.56, p(+55) =0.031 d=0.47 (1-sided). No significant differences were found in success rates of the image type (as shown in Table 3.2). Figure 3.8 summarises binomial test results in 33ms and 66ms conditions.

Reaction time data were skewed and non-normal, these data were transformed to follow a normal distribution using Logarithm and Reciprocal transformations. Data from same transformation were analysed and compared against each other. Reaction times at the different angles were paired and tested against reaction time in the control trials. Significant reaction time results within each angle are only taken into account when their success rate is significant. Reaction time alone cannot be used as a measure of priming effectiveness. No significant differences were found in reaction times of all angles that showed significant differences in success rates.

Cochran's Q test was conducted to compare stimulus types against each other in the two conditions. For the 33 ms duration condition, Cochran's Q showed that there was a significant difference in the proportion of successes between types at the angles -35, X2(2) = 9.238, p= 0.010 and -25, X2(2) = 13.300, p=0.001. Post-hoc analysis using McNemar's test on these angles was run to find where the differences occurred. Benjamini-Hochberg procedure was used to correct for multiple comparisons, with a false discovery rate of 10%. The angle -35 showed a statistically significant difference in the proportion of successes between the image and word stimuli, p= .007 d= 0.34 and the angle -25 showed a significant difference in the image and word stimuli, p= .003, d= -0.47 and in the shape and word stimuli, p= .004, d= 0.34. In all of these significant differences, the word stimuli showed higher success rates compared to images and shapes. No significant differences were found at any other angle in the 33 ms condition.

Stimulus types comparison was also conducted on the 66 ms condition. Cochran's Q showed

Table 3.1: p-values (1-tailed) of success rates and reaction times in 33 ms duration condition

			Horizontal Angle												
			-55	-45	-35	-25	-15	-5	0	+5	+15	+25	+35	+45	+55
Stimulus Type	Image	Success Rate	0.358	0.518	0.102	0.046[a]*	0.518	0.321	0.000	0.456	0.195	0.482	0.358	0.326	0.482
		Reaction Time	0.158	0.077	0.792	0.261	0.469	0.000	0.003	0.005	0.109	**0.033***	0.698	0.152	**0.006***
	Shape	Success Rate	0.298	0.298	0.451	0.015[a]*	0.388	0.006	0.006	0.479	0.174	0.298	0.134	0.244	0.174
		Reaction Time	0.22	0.155	0.386	0.019*	0.678	0.003	0.489	0.071	0.718	0.358	0.046*	0.033*	0.763
	Word	Success Rate	0.486	0.218	**0.000***	**0.001***	0.514	0.031	0.007	0.101	**0.022***	**0.008***	**0.008***	0.486	**0.008***
		Reaction Time	0.020*	0.825	0.295	0.378	0.530	0.006	0.173	0.08	0.098	0.027*	0.275	0.32	0.485

[a] Alternative hypothesis states that the observed proportion <test proportion.
* Significant at p <0.05.
Note: Bold value is significant using Benjamini-Hochberg procedure.
- Angles highlighted in grey indicate that the stimulus was visible at this angle.

that there was a significant difference in the proportion of successes between types at the angle +45, X2(2) = 7.500 p= 0.026. Benjamini-Hochberg procedure was applied in McNemar's test to correct for multiple comparisons (false discovery rate = 10%). Pairwise comparisons revealed that there was a statistical difference at the angle +45 between the image and shape stimuli, p=0.013, d= 0.22. Shapes had significantly higher success rates than images.

Reaction time data were transformed using two transformation functions. In stimulus type comparison, three reaction times (each belong to a stimulus type) were compared. However, data from the same transformation could not be compared against each other. Therefore, reaction times in stimulus type comparison were analysed using non-parametric Friedman test. Friedman test showed that there were no statistically significant differences in reaction times (at angles that showed significant differences in success rates) between stimulus types in 33 ms and 66 ms conditions.

Table 3.2: p-values (1-tailed) of success rates and reaction times in 66 ms duration condition

			Horizontal Angle												
			-55	-45	-35	-25	-15	-5	0	+5	+15	+25	+35	+45	+55
Stimulus Type	Image	Success Rate	0.032*	0.032*	0.423	0.152	0.152	0.009	0.000	0.123	0.075	0.154	0.152	0.423	0.272
		Reaction Time	0.382	0.701	0.601	0.078	0.356	0.000	0.000	0.000	0.978	0.061	0.094	**0.019***	0.542
	Shape	Success Rate	0.046[a]*	0.521	0.101	0.006	0.219	0.054	0.011	0.425	0.101	0.360	**0.019***	**0.006***	0.018[a]*
		Reaction Time	0.220	0.548	0.707	0.531	0.940	0.002	0.017	0.000	0.404	0.590	0.065	0.158	0.248
	Word	Success Rate	0.424	**0.031***	**0.004***	0.001	0.410	0.009	0.000	0.118	0.004	0.000	**0.031***	**0.011***	**0.031***
		Reaction Time	0.563	0.928	0.590	0.200	0.485	0.017	0.000	0.017	0.537	0.736	0.564	0.107	0.698

[a] Alternative hypothesis states that the observed proportion <test proportion.
* Significant at p <0.05.
Note: Bold value is significant using Benjamini-Hochberg procedure
- Angles highlighted in grey indicate that the stimulus was visible at this angle.

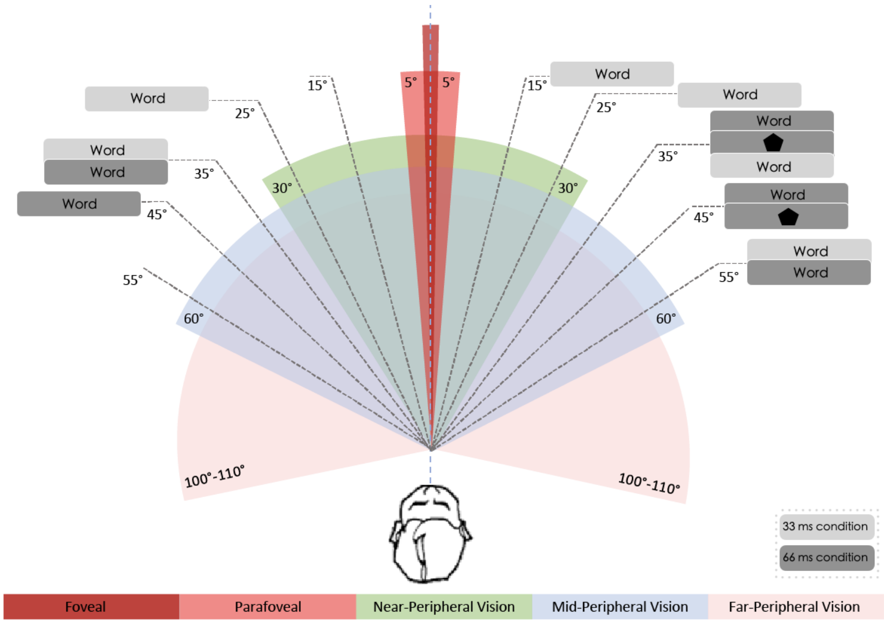


Figure 3.8: Results of the central and peripheral areas of the human visual field. The figure shows angle-level results in the 33ms and 66ms conditions (represented as light and dark grey boxes respectively). Words showed significant success rates at many peripheral angles in the 33 ms (-35, -25, +15, +25, +35, +55) and 66 ms (-45, -35, +35, +45, +55) conditions. Shapes showed significant success rates in the 66 ms condition at the angles +35 and +45

3.4.2.2 Between-subject analysis (presentation duration)

To analyse success/failure rates, each stimulus type in one condition was compared against the same type in the other condition, creating a 2x2 table for each horizontal angle in the mid peripheral area. Since stimuli that fell in the near-peripheral area in the 66 ms condition were visible, comparing it with the near-peripheral in the 33 ms condition was not possible and therefore this area was eliminated from the between-subject analysis. Chi-square tests showed that there were no significant differences in success/failure rates between stimulus presentation duration conditions at all angles in the mid peripheral area. Table 3.3 shows p-values for the studied angles.

Reaction times between conditions were compared using a Mann-Whitney test since comparing data from the same transformation against each other was not possible. Since none of the angles showed significant differences in success rates between duration conditions, significant reaction time results were not considered.

Table 3.3: p-values in Chi-square tests to compare success rates between conditions (33 ms, 66 ms) in the mid-peripheral area

		Horizontal Angle												
		-55	-45	-35	-25	-15	-5	0	+5	+15	+25	+35	+45	+55
Stimulus Type	Image	0.551	0.376	0.768	0.082	0.771	0.035	.[a]	0.673	0.149	0.242	1.000	0.771	0.383
	Shape	0.770	0.386	0.562	1.000	0.551	0.537	1.000	0.682	1.000	0.247	0.330	0.104	0.551
	Word	0.551	0.771	0.182	0.505	0.771	1.000	0.537	0.673	1.000	0.303	0.365	0.149	0.365

[a] No statistic is computed because all participants in 33ms and 66ms conditions were able to identify the stimulus at angle 0.
- Angles highlighted in grey indicate that the stimulus was visible at this angle.

3.4.3 Summary

Findings indicated that the priming effects (i.e., high success rates) in the word stimulus were found at many peripheral angles in the 33 ms (-35, -25, +15, +25, +35, +55) and 66 ms (-45, -35, +35, +45, +55) conditions. Angle level results of shapes showed significant success rates in the 66 ms condition at the angles +35 and +45 (See Figure 3.8). Type comparison results showed significant differences between image and word at -35 and -25, shape and word at -25 in the 33 ms condition, and a significant difference at +45 between image and shape in the 66 ms condition.

3.5 Discussion

Previous work in HCI have studied subliminal priming by presenting stimuli at the centre of the screen. In such setups, users are asked to focus on the centre of the screen in order to ensure that the stimulus is shown in the foveal vision (e.g., [11, 54, 236]). However, foveal presentations raise issues when aiming to use such subliminal stimuli in ambient displays, since these are perceived peripherally. Our understanding of the extent to which subliminal cues are effective at influencing decisions when presented in peripheral vision areas remains unclear. In addition, prior studies used both textual and graphical stimuli and it is unclear which type is more effective at influencing decisions/behaviours when presented in the periphery. This study addressed these gaps by examining the impact of different types of subliminal stimuli when presented in the periphery of our vision. This section discusses the findings in light of the research questions and summarises the gained insights.

RQ1: For each stimulus type, can the subliminal stimulus influence the selection performance when presented in peripheral vision areas? Figure 3.8 summarises the angle level results. The findings showed that subliminal stimuli can influence selection performance when presented at peripheral locations. The goal of the task used in the study was to assess the visual processing of the form of the stimuli and not assessing semantic processing, so it was expected that words would cause a slight influence on the selection performance because participants might need to process the meaning of the words (high-level analysis). However, words were shown to be effective at many peripheral angles in both duration conditions. Previous research found that textual subliminal stimuli were able to influence responses when they were presented in the parafoveal vision [138, 286]. This is inline with the finding in that subliminal words can induce priming effects even when not presented at the fixation point and further away from it. These results were found when the participants group included both native and non-native English speakers, it is possible that the word stimulus would cause a stronger effect if all participants were native English speakers.

Also, it was expected that the abstract shapes would influence responses since the bias caused by meaningful stimuli is reduced, but this was not supported in the results. In addition, unexpected selection performance was shown in images when no priming effects were shown in both conditions. This result along with previous work that showed priming effects in subliminal graphical stimuli, presented in the parafoveal area [22, 264] suggest that graphical stimuli could be effective in the periphery, further work is needed to investigate subliminal graphical stimuli in the periphery.

The reasons for these results could be related to three factors. First, it is possible that the results were affected by how the brain processes information located in different areas of the visual field, as the left visual field is processed using the right cerebral hemisphere whereas the left cerebral hemisphere processes information shown in the right visual field [42]. Studies have also shown that each hemisphere play an important and different role in language processing [98, 248, 308], however, the left hemisphere dominance for language processing is high relative to right hemisphere [316]. It is possible that the presence of more significant differences in the word stimuli in the right angles of the visual field are because subliminal words were processed by the left hemisphere which is mainly responsible for language processing [316]. This suggests that the left hemisphere dominance of language can also be found in the processing of the subliminal word stimuli occurring in the right visual field. This also explains the the absence of significant differences in the word stimuli in some of the left angles as they were processed using the right hemisphere. Second, since the stimulus complexity affects the unconscious processing of the subliminal stimuli [278], it is possible that images and shapes, although simple black and white line drawings, were more complex to process subliminally than the short and highly familiar words. Also, since no high processing level (i.e., semantic) was required in the given task, it is possible that the perceptual processing (form) of words was easier to detect than images and shapes. Third, it is possible that the findings were affected by the experimental settings tested. For example, the specific duration used between the subliminal stimuli and the questions might have resulted in difficulty in processing the stimuli such as image and shapes. It is possible that complex stimuli require shorter durations between the stimulus and the task. Further experimental work is required to test and generalise these results in different experimental manipulations.

RQ2: Which stimulus type shows better selection performance at the peripheral angles? Results revealed that some peripheral angles showed significant differences in success rates between the word stimulus and the other types. Particularly, the word stimulus performed better (i.e., higher success rates) than the other types at two peripheral angles in 33 ms condition. The reason for this result may be due to the complexity of the graphical stimuli, and that they were more complex to be processed subliminally than textual stimuli, as complex stimuli can reduce the priming effects [278]. It is also possible that the selected familiarity level of the word stimuli have rendered them being easier to process compared to graphical stimuli. Another reason that relates to the geometric shapes stimuli could be attributed to difficulties in distinguishing the abstract shapes as they are more similar to each other compared to the word stimuli. Even though the polygons compared in the priming task were of different point sizes, it is possible that participants were unable to identify the subliminal stimulus due to similarities found in the shown stimuli. Although some peripheral angles showed significant differences between types, it cannot be confirmed that the textual stimuli are more effective than graphical stimuli in all other peripheral areas. The results in binomial tests showed more priming effects in the word stimulus, however, the difference was not significant in type comparisons using Cochran's Q test. A previous study compared textual and graphical subliminal stimuli; presented centrally, in a perceptual priming task and found that both types showed priming effects [159]. Additionally, previous work showed priming effects for both textual [138, 286] and graphical [22, 264] stimuli in parafoveal area. Therefore, the finding that textual stimuli are better than graphical stimuli at all peripheral locations cannot be generalised. Further studies are needed to investigate whether processing of types differs in peripheral areas.

RQ3: Which presentation duration is more effective for peripheral subliminal presentations? The findings showed no significant differences between the long presentation duration condition and the short presentation duration condition. Schmidt et al. [265] reports that using very short presentation durations could degrade the stimulus signal and as result, diminish the priming effect. In addition, previous studies suggest the use of longer presentation durations when presenting subliminal stimuli out of the focal point to ensure that stimuli do not fall below the priming threshold [25, 265, 276]. Based on that, it was expected that long presentation durations would result in a better selection performance compared to short presentation durations in peripheral areas since the stimuli might occur within the priming threshold. However, it cannot be confirmed that long presentation duartions performed better than short duartions in peripheral areas. In previous work, Bar et al. [22] used an average duration of 47ms for subliminal presentations in the parafoveal vision, thus it is possible that the 66ms presentation duration was not long enough to induce significant differences in selection performance from the

33ms duration in peripheral vision areas. Further investigation is needed to find a duration that can be used in peripheral areas and fall within the priming threshold. Future studies should also investigate whether each visual field area requires a different presentation duration. Identifying the user's central/peripheral area and adjusting the presentation duration accordingly should be possible in the future since camera-based eye tracking are becoming available and it is expected that eye tracking will be embedded in many display environments [122, 139].

Although the results showed priming effects in a number of visual angles in the word stimulus, the inconsistencies in the influence of the subliminal stimuli on decision-making make them not appropriate for ambient technologies. This is because it would require designing ambient technologies that display specific type (i.e. word) at specific visual angle and at a certain presentation duration to influence users' decisions. For example, the word stimuli can be presented at the angle +15° with a 33 ms presentation duration but cannot be presented at -15°. Also, presenting a word stimulus at the angle -25° requires a presentation duration of 33 ms, while presenting it at the angle -45° requires 66 ms presentation duration. Therefore, this leads to the conclusion that such low-level cues are not suitable for practical applications (i.e. influencing decisions using ambient technologies) and hence there is a need to examine higher cue levels to influence decision-making.

Ethical Considerations The use of subliminal priming in systems introduces important ethical considerations. A critical ethical concern is raised around their use without the user's knowledge. In persuasive applications particularly, this can be considered a major threat to individual autonomy and free will values. For example, a system that subliminally persuades people to eat unhealthy food or buy a particular product could jeopardise autonomy since the user is unaware of the use of subliminal stimuli nor the delivered message and hence cannot evaluate the message and decide. Regardless of the application domain, I strongly believe that users should always be aware of the use of subliminal priming in systems. Designers must clearly inform the user about the purpose of such subliminal stimuli, how they are presented, and their consequences before using the system.

While the main aim of subliminal priming examined in this study is to provide support in changing behaviours for the benefit of the user, they can be used in the service of unethical and manipulative aims. A key concern here is when designers implement such techniques with deceptive goals that choose the shareholder's interests over the user's interests (i.e., dark patterns) [115]. For example, manipulating the user interface by embedding subliminal stimuli to influence and encourage users to purchase more products (unethical marketing). When dealing with using subliminal priming as a dark patterns strategy, it is essential to emphasise on the role of design responsibility in addressing their ethical issues [115]. Designers should base their designs on core values (e.g., avoid deception, support autonomy) to ensure ethically responsible designs [100, 115].

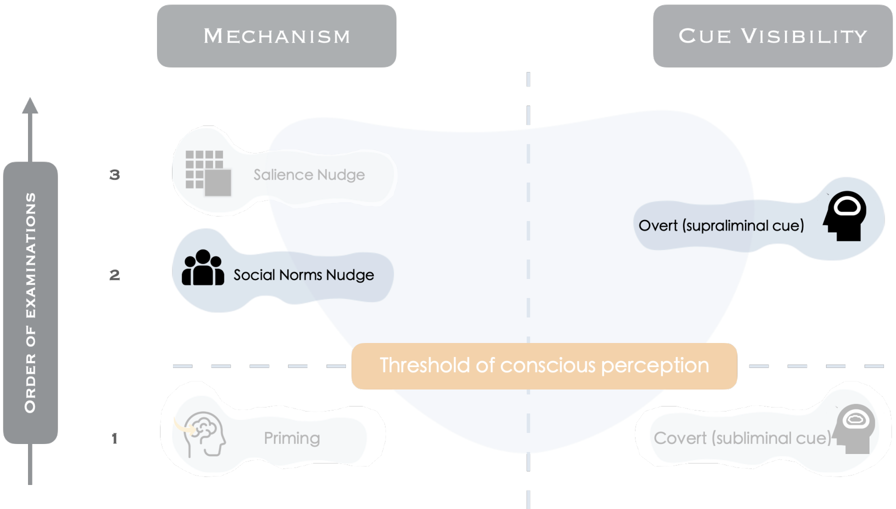
Limitations The results are limited to cases where perceptual priming (i.e., concerned with the form of the stimulus) is employed. It remains unclear whether these results would apply to other priming tasks, stimulus types and presentation durations. Another source of uncertainty is the impact of the task used on the results. Research has shown that the nature of the task influences the perception of the subliminal stimuli [160, 181, 238] and it is possible that this has affected the findings. In addition, while I carefully selected non-affective image and word stimuli for this study, a potential uncontrolled factor that could have occurred is the possibility that some participants might have found certain stimuli affective, which could influence subsequent judgements [129, 183, 216] and hence affect the findings. Also, a limitation of the experimental setup is that the focus on the fixation point was controlled by giving instructions to participants before starting the study, as done in [122]. Although the researcher had observed the setting carefully to eliminate head or eye movements, it is possible that few unintentional movements had occurred during the study.

3.6 Conclusion

In this chapter, I investigated whether and how subliminal cues, which fall below the threshold of conscious perception, influence decision-making using the Priming mechanism. In a controlled study, I examined three types of subliminal cues, presented at thirteen visual angles and tested using two presentation durations and how they influence decision-making. I gained a new understanding into the use of peripheral subliminal cues in influencing decision-making. I showed that while there is significant effects of certain subliminal cues types, presented at specific visual angles and presentation durations, on decision-making, the inconsistency in these findings make using them in applications particularly challenging. I concluded that peripheral subliminal cues may not suitable for use in ambient technologies. Hence, I explore in the next chapter a higher cue level; supraliminal cues, which can be delivered through the nudging approach. The next chapter particularly examines the Social Norms nudging mechanism and how the supraliminal social cues it employs can be designed.

Chapter 4 & Chapter 5

Social Norms Mechanism with Supraliminal Cues



CHAPTER 4

UNDERSTANDING & DESIGNING SOCIAL CUES FOR FLOOR INTERFACES

THIS CHAPTER:

- Presents a study demonstrating how different floor visualisations that show traces of navigation behaviour affect navigational decisions and how they are interpreted.
- Describes a design study exploring the challenges highlighted in the first study and investigates how floor interfaces that show social cues could work in practice.
- Provides a set of design opportunities and novel insights into the design of "history-enriched" floor interfaces.

I have published the studies presented in this chapter in [C.1] and [E.1].

4.1 Introduction

The results reported in Chapter 3 demonstrate that peripheral subliminal cues may not be suitable for ambient technologies. Therefore, a higher cue level (i.e. supraliminal cue) is needed to unobtrusively influence decision-making. Such supraliminal cues can be delivered through the use of nudging as an approach to impact decision-making in a subtle way. There exists a number of nudging mechanisms that leverage individuals' cognitive biases and hence, can be used to affect decisions. I focus in this thesis particularly on influencing navigational decision-making.

By examining how people solve navigational problems and make navigational decisions while exploring unfamiliar environments, a number of heuristics and cognitive biases, which people employ to facilitate their navigational decision-making, can be found. For example, research has shown that the presence and/or actions of other people have a noticeable influence on our navigational decisions [77]. People's tendency to conform and follow behaviours of other people is known as social norms bias [63, 77, 297]. While such bias has been utilised extensively in indirectly guiding people while navigating information spaces [89, 90] as well as in navigating outdoor spaces using location-based social services [31, 96, 134], there is a lack of technologies, particularly ambient technologies, that utilise this social norms nudging mechanism and the social cues it employs (i.e. navigation traces of other people) to facilitate and guide navigational decision-making implicitly in indoor spaces.

In this chapter, I use the social norms nudging mechanism with social cues in floor interfaces. I particularly explore a new usage of interactive floor interfaces and investigate how they can be designed and used to visualise, present and integrate social cues into indoor spaces, and whether and how they would affect people's navigational decisions when such social cues accumulate. I call this new usage of interactive floors *history-enriched floor interfaces*, i.e. floor interfaces that show navigational traces of previous users. Such floor interfaces are considered ambient technologies as they move from the centre of attention to the periphery and integrate with the environment without negatively affecting the user' s primary task of navigation. To investigate their design, I carry out two studies:

The first study examines six visualisations of navigation traces to understand how social cues affect people's decisions, and how they are interpreted.

The second study engages potential users in designing solutions that address the challenges highlighted in the first study and investigates how such floor interfaces could work in practice. Building on the results of the first study, the footprints visualisation is used in the implementation of an interactive floor display that tracks and displays the user's footprints. This system is used as a technological probe during individual design sessions with twenty-six participants.

The chapter ends with a discussion of the findings and a discussion of design opportunities for history-enriched floor interfaces.

4.2 Background

4.2.1 Interactive Floor Systems

Much of the HCI research on floor displays has focused on supporting interactions with the display. These studies have investigated different implementation methods of interactive floors (i.e. sensor-based or vision-based), interaction techniques, user identification and ways to expand the display area [14, 44, 81, 119, 213]. So far, interactive floor displays have been used mainly in entertainment and multi-user collaborative applications(e.g. [119, 172]). There has been less research, however, on how to utilise them in other application domains. Recently, researchers have proposed to use interactive floors as an assistive display [315], behaviour change tool [251] and as an ambient display to promote situational awareness [207]. In addition, efforts have been made to support navigation using floor displays (e.g. [224, 256, 336]). While these efforts uncover many of the potentials of floor displays, using floor interfaces as an ambient display for influencing and nudging navigational decision-making using social cues remains largely unexplored.

4.3 Study 1: Visualisation Ideation and Evaluation

To explore how to visualise, present and integrate asynchronous social cues digitally into public spaces and particularly on interactive floors, different visualisations of traces of navigation behaviour were examined. There were six different visualisations: time difference, heatmap, dots, footsteps, line type and lines as shown in Figure 4.1. These visualisations were generated during a 15 minutes brainstorming session, with eight participants split into two groups, conducted prior to this study. They were asked to generate sketches that represent *"traces of navigation behaviour"*. After 15 minutes of brainstorming, each group was asked to present their ideas and select their three best ideas. A list of all the generated ideas is presented in Appendix B.1. The best ideas generated by the groups were used in the next study. Participants in one of the groups mentioned that the dots visualisation was inspired from Vermeulen et al.'s [315] and Monastero et al.'s [207] work on floor interfaces.

The study presented below examines whether and how the *accumulation* of social cues affects navigational decisions, and explores how people interpret the visualisations. Ethics approval was obtained from the university's ethics committee before conducting the study.

4.3.1 Method

4.3.1.1 Participants

Twelve participants (7 female), aged between 19 and 27 years (M= 22.5 SD = 3) were recruited to contribute to the study. They were recruited in person and via posters at my institution. Participants were a mixture of Engineering staff and students. They were offered non-monetary reward at the end of the study.

4.3.1.2 Setup

The study took place in a lab space at my institution. Participants were facing a large projected display, as shown in Figure 4.2. A short-throw projector (BenQ MW864UST, running at

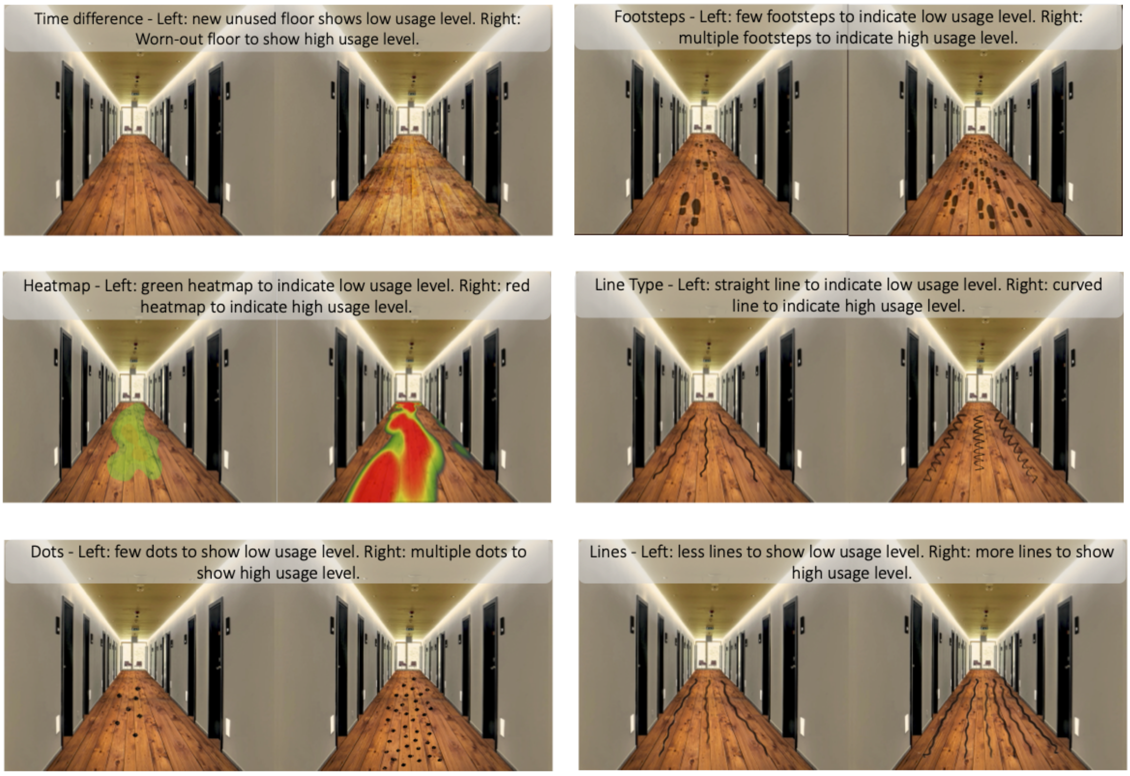


Figure 4.1: Selected visualisations to represent traces of navigation behaviour of other people include time difference, footsteps, heatmap, line type, dots and lines.

1920x1080p resolution) was used. The images of the two corridors were projected on a wall in front of the participants so that the image were 1.5 meters high. This setup was chosen to mimic a real navigation situation and to approach real corridor scale seen from the participants point of view.

4.3.1.3 Task

To explore the effect of different social cues visualisations on users, a building navigation task was created where participants were shown two corridors, one showing a high usage level (many traces) and the other showing low usage level (few traces) in the selected six visualisations. The building navigation task was projected on a wall in front of the user in order to mimic navigation in real setup and scale. The participants had to choose one and explain their rationale.

4.3.1.4 Procedure

Upon arrival, participants were given an overview of the study and were then asked to complete the consent form and demographics questionnaire. Structured interviews were conducted with

Figure 4.2: Experimental setup of Study 1.

participants to evaluate the selected visualisations (Figure 4.1). Participants were asked to answer questions given by the researcher (See Appendix B.2) verbally while facing the visualisations (Figure 4.2). In the first part of the interview, an indoor navigation scenario was presented and participants were asked to select their path choices and justify their decisions in six different situations. Next, participants were asked to provide their own interpretation of the meaning of each visualisation. Then, participants were told that the the shown visualisations were selected to represent navigation traces of previous people, and they were asked to rank the top three that they thought presented this information in the most meaningful way. Finally, they were asked to suggest other visualisations if they have any. The researcher took written notes of the participants' answers. The interview took approximately 15 minutes to complete.

4.3.1.5 Data Collection and Analysis

Notes were taken and participant's answers were recorded on pre-formatted answer sheets. The frequency of navigation choices for each of the selected visualisation was analysed. Thematic analysis with an inductive coding approach was employed to analyse participants' justification of their path choices. The interview was first read and openly coded. Following this, peer validation was conducted throughout the coding process with an additional researcher to review and clarify codes and emerging themes. The qualitative data analysis software, NVivo was used to thematically analyse the data. Visualisation ranking was analysed by calculating frequency of responses and applying different weights for each of the choices.

4.3.2 Results

4.3.2.1 Frequency and justification of navigation choices

The frequency of path choices for each of the selected visualisations was analysed, as shown in Figure 4.3. Thematic analysis then produced three themes that describe the factors that influenced participants' path choices: selection based on a self-centred point of view, selection based on environmental features, selection based on usage and navigational traces.

Theme 1: Selection based on a self-centred point of view
Participants expressed feelings towards the visualisations (n=7). Some participants described paths as *"scary"(P10), "isolated"(P6)*, while others described paths more positively *"safe"*(P3), *"comfy"*(P2), *"assuring"*(P11). P8 described the path with more footprints as *"lively"* compared to the *"lonely"* path with less footprints.
Participants explained that the floor visualisations triggered their curiosity and interest to take a specific path (n=4). Participants reported that some paths are *"more interesting"* (P4) and that some visualisations showed that *"something is happening"* (P7). P4 stated that a path with more footsteps is more interesting to explore.

Theme 2: Selection based on environmental features
Participants described the environmental aesthetics of the scenes to explain their navigational choices (n=11). For instance, participants reported that some paths are *"nice"*(P1), *"clean"*(P6) and *"natural"*(P7). P10 described the new floor as *"sleeker floor"* compared to the old worn-out floor. Other participants reported avoiding *"messy"*(P12) paths.
Also, participants expressed that their path choices were based on abstract visual features of the floor visualisation (n=8). For example, paths were described as having *"smaller red spot"*(P9) and *"straight lines"*(P4). P1 reported that she avoided the path that contained *"too many lines"*.
P2 described the dimensions of the shown scene and reported that her path choice in the time difference visualisation was due to width of the path.

Theme 3: Selection based on usage and navigational traces
Participants expressed that path usage and navigational traces have influenced their navigation choices (n=10), where n is the number of participants who reported usage in at least one visualisation. Some participants preferred to select paths that show high usage level while others chose to select paths with low usage level to avoid other people. For example, participants explained that their choices were because paths showed *"more traces"* (P9) *"more footprints"* (P1) and *"more people"*(P3). On the other hand, some participants reported taking the paths that are *"used less"* (P8) in order to *"avoid crowds"* (P11).

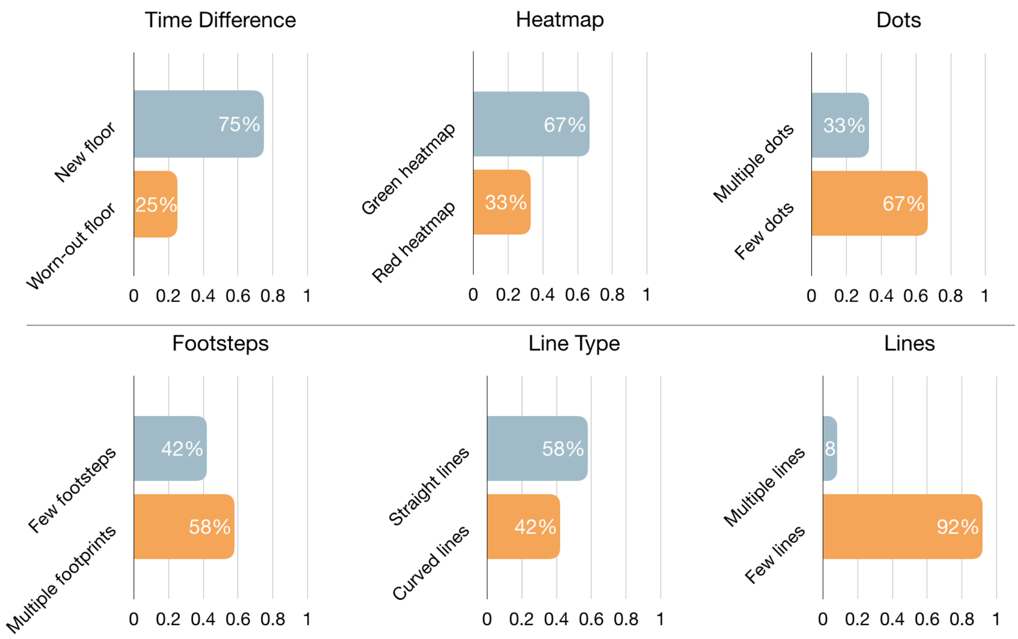


Figure 4.3: Participants' path choices in the selected visualisations.

4.3.2.2 Visualisation interpretation

Thematic analysis also included extracting themes that capture how people interpret the floor visualisations. Two main themes emerged: provision of information and abstract interpretations.

Theme 1: Provision of information

This theme describes the information that the visualisation provides including the actions that occurred in a path, usage information, time difference, temperature and cleanliness level. Participants described specific actions that occurred in the paths (n=4). P12 described the lines visualisation as *"dragging things on the floor"* while P4 reported a *"bouncing ball"* in the line type visualisation. Another longer term activity reported by participants was walking. Many participants (n=11) expressed the meaning of the visualisations in terms of path usage (i.e. number of people, walking direction, movement type). P3 reported that the footsteps visualisation means that *"more people are walking*. P12 reported that the heatmap visualisation shows where people have travelled. P9 pointed out that the line type visualisation represents different kinds of movements.

Also, participants reported that visualisations provided other information about the state of the path in the time difference visualisation, temperature in the heatmap visualisation and cleanliness level in the dots visualisation.

Theme 2: Abstract interpretations

Many participants (n=9) used abstract descriptors that do not consider the given navigation context to interpret the visualisations. For example, animals were reported by participants in

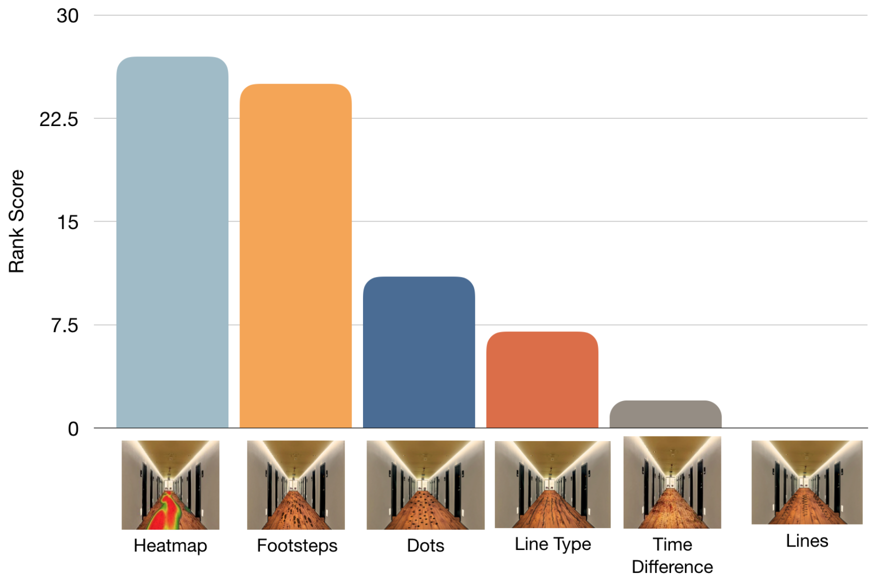


Figure 4.4: Participants' ranking of the six visualisations shows that the heatmap, footsteps and dots are the top three visualisations that best represent traces of navigation behaviour.

different floor visualisations *"ants"* (P1), *"dogs"* (P5) and *"snake"* (P2). Other descriptions reported by participants included *"blood"*, *"monster"*, *"graffiti"* and *"art"*.

Four visualisations were described by at least three participants using abstract descriptions. In particular, five and seven participants reported abstract descriptions in the heatmap and dots visualisation respectively. Visualisations such as time difference and footprints were found to be informative by all participants.

4.3.2.3 Visualisations ranking

Participants were asked to rank their top three visualisations that best represent traces of navigation behaviour of other people. The heatmap visualisation was selected by participants as their top choice followed by footsteps and then the dots visualisation. Figure 4.4 shows the ranking scores of the six visualisations.

4.3.3 Discussion

This study resulted in a number of useful insights that will guide the next investigation of the design of history-enriched floor interfaces. The study provided an understanding of the effect of social cues on navigation decisions. Surprisingly, the results showed that usage and navigational traces was not the only factor that affected participants' navigation decisions. Feelings, preferences and other environmental features also play an important role in their decisions. This suggests that social information such as navigation traces will not always guide peoples' navigational decisions. Designers need to take into consideration the impact of the other factors when designing history-enriched floor interfaces.

The themes extracted to understand how people interpret the visualisations show that *direct* and clear visualisations that represent navigation traces is crucial. In some visualisations (e.g. heatmaps and dots), participants reported abstract interpretations and were unable to infer the information provided in the visualisation.

Although the heatmap visualisations was rated as the top choice by participants to represent traces of navigation behaviour of other people, visualisation interpretation results showed that participants interpreted it using abstract descriptions. This shows that the heatmap visualisation may not be straightforward enough for many people. On the other hand, the footprints visualisation was ranked as the second choice and was found informative by all participants. This suggests that the footprints visualisation is a direct and an easy-to-understand representation of navigational traces.

In addition to those findings, this study uncover a series of challenges in the design of history-enriched floor interfaces:

Visual representation and its features. Visualisation misunderstanding and the use of abstract interpretations was a result of vague link between navigational traces and the chosen visual representation. In order to reduce the chances of misinterpretations, an in-depth understanding of the visual features of the selected representation is needed.

Representation of multiple people. Another challenge in the design of such interfaces is how to represent multiple people in the same space. In visualisations such as dots and lines, participants used abstract descriptions (e.g. animals and graffiti) and were unable to extract useful information. One possible reason could be because the visualisation used the same colour to represent information about multiple people. Adding colour, for instance, could help in reducing such interpretations.

Designing more prominent visualisations. Information shown on the floor could sometimes go unnoticed [207]. Also, the findings showed that the floor visualisation competes with other factors when making our navigational decisions. Hence, a crucial design challenge that should be considered is how to make floor visualisations more prominent and increase the chances of them being noticed.

Incorporation of non-identifying information about previous people. The findings showed that participants made their navigational decisions based on usage and navigational traces. Although the accumulation of social cues have affected participants' navigational decisions in different ways, adding additional information, apart from movement direction, to the navigational traces would help in making more informed navigational decisions. It is thus important to investigate what and how to incorporate additional non-identifying information about previous people in these social cues to support exploration and navigation in public spaces.

The second study investigates these challenges further through the use of design activities.

4.3.3.1 Limitations

One limitation of this study arises from the design of the visualisations. It is possible that the findings of this study were affected by the different number of pixels and the contrast levels in each of the designs. It is also possible that using a colour in one of the visualisations (heatmap) might have affected the outcome of the study.

4.4 Study 2: Design Sessions

Following the first study and the learned lessons, design sessions were conducted to engage potential users in designing potential solutions to the challenges identified in Study 1. First, an interactive floor system was implemented and used as a probe during individual design sessions. The design sessions focused on examining the four design challenges identified earlier: visual representation and its features, representing multiple people in the same space, making floor visualisations more prominent and incorporating additional non-identifying information about previous people that can help in navigating spaces. Individual sessions were conducted rather than group sessions because on the one hand there is a need to examine the impact of these visualisation on individual path choice behaviour, and on the other, to allow for a feasible design setup where each participant can explore and interact with the interactive floor system. Ethics approval was obtained from the university's ethics committee before carrying out the design session.

4.4.1 Method

4.4.1.1 Participants

Twenty-six participants (12 female), aged between 19-30 years (M = 21.7, SD= 2.5), were recruited from my university. Participants were different from Study 1 participants. Participants were a mixture of staff and students. Twenty-four participants had a background in Engineering while two participants stated having a background in Psychology and Finance respectively. Participants were compensated with a gift voucher at the end of the study.

4.4.1.2 Setup

An interactive floor system that covers an area of 1.8m x 3.2m was developed. The floor system consists of a Microsoft Kinect camera and a short-throw projector (BenQ MW864UST, running

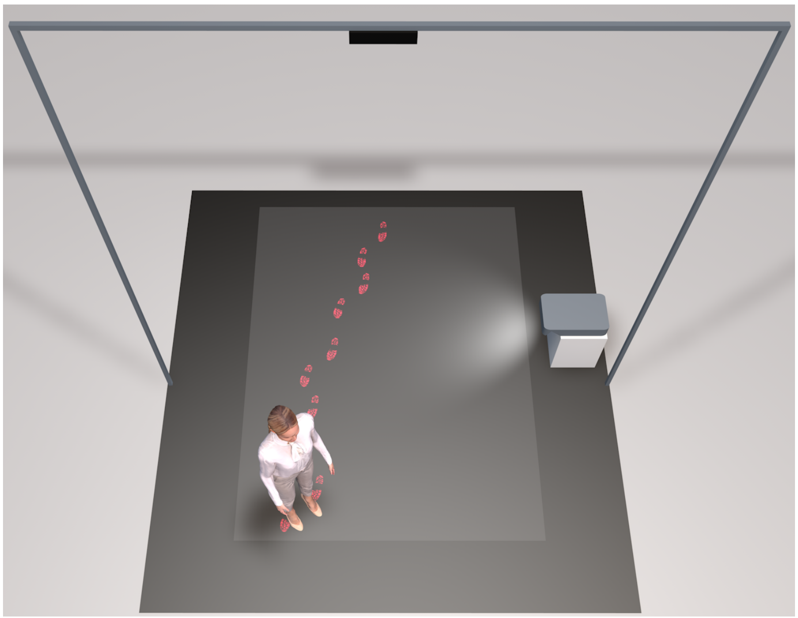


Figure 4.5: An Interactive floor system implemented as a technological probe during the design sessions.

at 1920x1080p resolution). The system tracks the participant's movement and projects their footprints on the floor, as shown in Figure 4.5. The system assigns a different colour of footprints for each user. The created footprints fade away after five minutes of creation.

4.4.1.3 Procedure

The design sessions took place in a research lab and lasted for an average of 30 minutes per participant. To begin, participants were given an overview about the study and were then asked to sign consent forms and fill a demographics questionnaire. Next, participants were asked to use and interact with the system before starting the design activity. Participants were provided with different materials such as inspirational photos, design activity sheets, post-it notes and coloured pens, as shown in Figure 4.6. To initiate the design activity, different photos of public spaces (e.g. museums, art galleries) and human footprints in different environmental conditions were presented. Then, participants were given a drawing warm-up activity. Following that, the facilitator presented participants with a scenario about the use of the system in a museum setting and participants were asked to brainstorm and design visualisations in each of the aforementioned design challenges. A copy of the design activity can be found in Appendix B.3. Participants were asked to express the ideas by writing or drawing them on the given design sheets and to explain them verbally if further explanation was needed. Participants were asked to explain the generated design ideas after completing each design aspect. Figure 4.7 shows a participant during the design session.

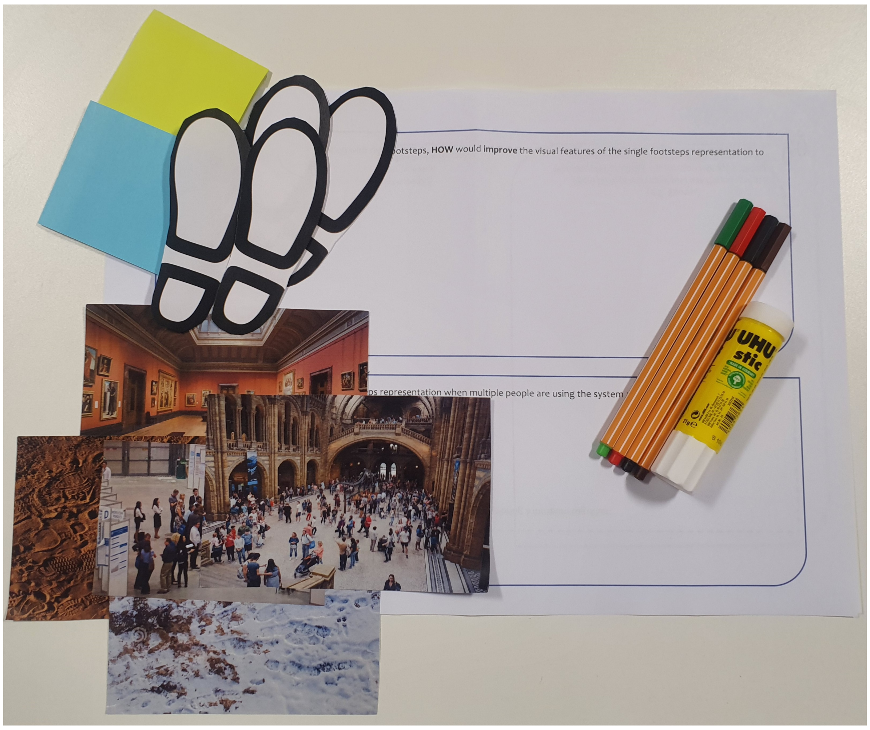


Figure 4.6: Design activity materials.

4.4.1.4 Data Collection and Analysis

The design sessions were video-recorded and the designs produced by the participants were collected for later analysis. All participants reported the generated ideas on the design sheets. Thematic analysis with an inductive approach was used to code and analyse the data. Design ideas were first read and openly coded. Then, peer validation was conducted with two additional researchers to review codes and emerging themes.

4.4.2 Results

The themes that were generated in each of the design aspects are reported below. Overall, participants generated 80 unique ideas in the four design challenges (See Appendix B.4). Ideas that occurred repeatedly across participants were grouped into one. Ideas that were out of the scope of the design task were eliminated. Figure 4.8 shows examples of the ideas that the participants generated.

4.4.2.1 Visual representation and its features

In this sub activity, participants were asked to think of ways to examine the visual features of the current visualisation design used in the system and explore how it could be improved. Design ideas were found to be falling under three themes: (1) Realistic designs; (2) Aesthetically pleasing

Figure 4.7: A participant is engaged in the design activity.

designs (3) Not requiring any changes to the current visualisation. Three participants generated ideas in two of these categories. Several participants (n=12) focused on improving the design by generating more realistic design ideas. For example, P8,P4 and P23 suggested that the footprints should have more diversity in size, stride, types and shape. Participants also proposed visualising the exact gait of the user (P12 and P13). P16 suggested that such footprints should have a *"3D feel"* to create foot imprints that show different weights.

In addition, many participants (n=9) focused on generating attractive and aesthetically appealing designs. For instance, P10 and P14 proposed using simple and clean designs such as showing only the contour of the footprint and using soft footprints colours. P1 suggested using more eye-catching and more illuminated designs.

Four participants found the current visualisation design satisfactory and did not suggest any additional improvements.

4.4.2.2 Representing multiple people in the same space

Participants were asked to design a floor visualisation that can be used to represent different people in the same space. Two themes were identified in the generated design ideas. The first theme focused on representing each individual in the space differently. For example, many participants (n= 18) proposed introducing variations in the footprints colours, patterns and sizes. P15 suggested personalising her own visualisation and using user-defined shapes or symbols.

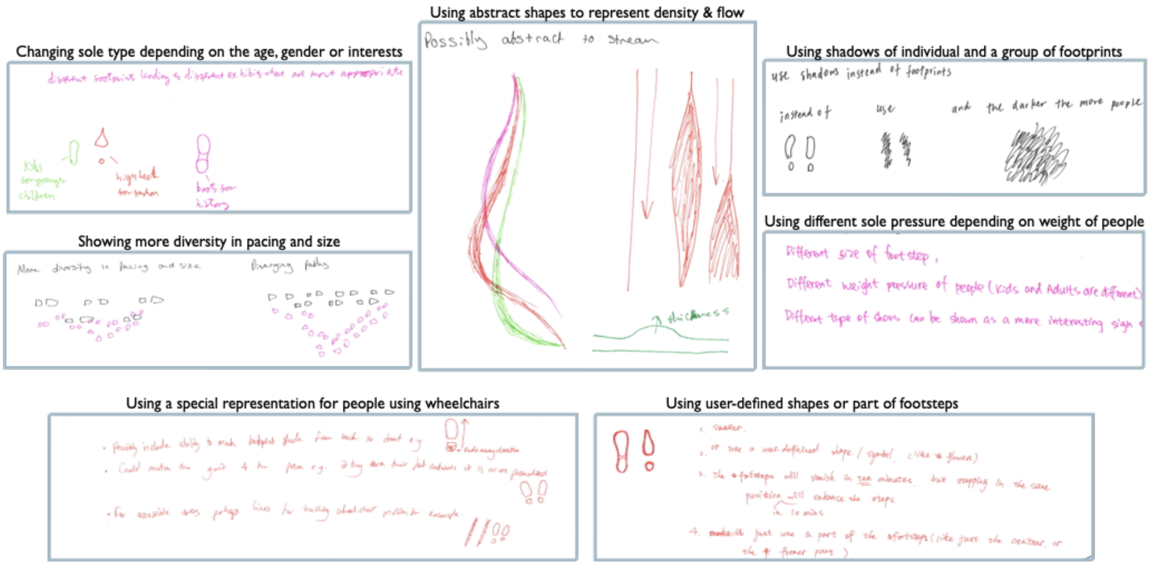


Figure 4.8: Examples of design ideas generated by participants.

The second theme of designs focused on visualisations that reflect the average movement of visitors and not the individual movements (n=9). For instance, P1 suggested the use of a single *"beam"* that shows different brightness levels depending on previous visitors' activity. Similarly, P8 designed a single line with varying thickness to represent the previous activity (Figure 4.8). Also, P6 suggested combining activity information and creating a *"super large feet"*.

4.4.2.3 Making floor visualisations more prominent

In this task, participants were asked to incorporate features to make floor visualisations more prominent and noticeable. Ideas generated in this task fall into three themes: (1) Using dynamic visualisation designs; (2) Introducing additional feedback modality; (3) Machine learning and prediction.

Several participants (n=13) proposed changing shapes, colours and brightness levels in response to certain actions. For example, participants suggested using vibrant and bright colours of the visualisation when it is first created and reducing the brightness level with time. P6, P11 and P19 suggested shrinking the footprints visualisation gradually over time until it disappears completely. P10 suggested to animate the footprints *"walking"* periodically to attract the attention of the passerby. Two participants suggested incorporating animation effects when a user steps on another user's footprints (e.g. erasing or animating the previous footprints).

Four participants proposed the use of the additional feedback modality to notify users about the interactive floor. For example, P1, P21 suggested providing auditory feedback (e.g. tapping sound) and vibration respectively when the user walks on the interactive floor.

Finally, P24 suggested using machine learning to study interests and navigation behaviours of people and then suggest paths and areas to check during their visit.

4.4.2.4 Incorporating additional non-identifying information about previous people

The current footprint visualisation shows only the direction of movement, so participants were asked to think of additional non-identifying information that would be useful for them when they navigate spaces. One of the most recurrent information was age (n=21). Participants proposed representing age by changing colours or sizes of footprints.

Four participants also suggested that previous visitors' interests and specialisation could help them visit the areas of people with similar interests. This could be done by creating a set of predefined colour codes for each specialisation.

In addition, P7 proposed showing what other people like in the space (i.e. *"Likes"*) which can be added as a tag to the footprints visualisation by double tapping the floor display.

P15 and P4 suggested adding information about the familiarity of the space, i.e. first time or regular visitor.

Additionally, P4 and P24 proposed including information of whether they visited the space individually or as a group.

Participants also pointed out that the time spent at the different locations within the space help them in assessing the importance of what is on display at that location. In this case, time spent can be represented by providing more emphasis on the colours or by differentiating the shape of the floor visualisation (e.g. bigger as the time spent increases).

4.4.3 Discussion

Despite the important role that information about other people plays in supporting navigational decision-making in public spaces, limited efforts have been made to utilise and embed such social cues in these spaces to support exploration and navigation. Thus, the studies described here examined how social cues can be visualised and integrated into indoor environments and whether and how they impact navigational decisions when they accumulate. This is achieved by first carrying out a study to ideate and evaluate floor visualisations and then conducting design sessions to examine the key design challenges identified in Study 1. Study 1 and Study 2 contribute to understanding how history-enriched floor interfaces could be designed using the social norms nudging mechanism to guide and influence navigational decision-making in indoor spaces.

Design sessions have provided valuable insights into the design of history-enriched floor interfaces. When assessing the visual representation and features of the implemented footprints visualisation, participants reported that the visualisation should reflect the user's footprints in terms of size, type or shape. While others found that it is important to make the visualisation attractive by using simple designs. This suggests that both realistic and aesthetically pleasing designs are crucial features in the design of navigational traces. Reflecting variety in footprints would ensure that people interpret it as traces that belong to other people and not as artificial footprints (e.g. stickers on the floor) that are usually used to guide people to certain locations within buildings. Therefore, *designers need to consider reflecting the features of natural traces while maintaining simplicity and clarity in their design.*

Representing navigational traces of previous people using floor displays is challenging. Participants proposed to uniquely identify each user by using different colours, patterns or user-defined symbols. Prior work have also used colour-coding for multi-user floor systems [207, 315]. However, a group of participants raised concerns regarding the lack of clarity that could occur if each person is represented individually and instead they proposed to design an aggregated representation of individuals. For example, aggregations can be represented using a line visualisation where the thickness of the line increases slightly each time someone uses that path or spends some time at a certain location. Clearly, the lack of clarity would become an issue when number of people available in the space exceeds a certain threshold. In this case, designers can design the system so that each person is identified uniquely (i.e. representing individual experiences) but once number of people reaches a certain limit, these social trails are averaged and aggregated to reflect collective experiences. *By identifying the type of environment that the system would be deployed in and the average number of visitors, designers can also choose to implement the system either by representing individual or aggregated social cues.* Further investigations should examine whether and how these representations (i.e. individual and aggregated) affect navigational decisions differently.

It is possible that floor interfaces get unnoticed or ignored by people [207] and hence limiting their effectiveness. Vermeulen et al. [315] demonstrated that using coloured floor halos (an area of 1m diameter) to notify users about the interactive floor have made participants aware of the floor display and their interactions with it. Participants proposed interesting ways in order to direct the attention of the passerby to the floor display. *Designers can use dynamic visualisations such as changing colours or sizes in response to certain events or they can use additional feedback modality (e.g. audio) to notify users about the floor display*. Certainly, the selection of the notification measure depends on the environment that the system will be deployed in. For instance, auditory feedback might be obtrusive and inappropriate to use in certain spaces.

Besides showing the direction of movement, such social cues can become more useful if they show an additional layer of non-identifying information about other people's navigation experiences. Participants proposed to incorporate information such as age, interests, likes, visitor's familiarity of the space and group size to help them filter the experiences that do not suit them. Categories of these information can be presented by colour-coding footprints. Interpretations of colour codes should be available for visitors upon entry of the space by, for example, displaying them on public displays. *Depending on the context, designers can consider incorporating such additional information to support exploration and navigation of the public space.* Future work should examine methods to obtain these information from visitors as well as ways to show and explain codes interpretations to visitors.

Finally, design has become common practice in technology design in the past few years [261]. Future users can now participate in the process, share their views and cooperate creatively to generate novel designs [283]. The design approach followed have brought new perspective on the design of history-enriched floor interfaces and have enabled us to gain an understanding of users' needs. The creative ideas that the participants have generated provide useful insights to designers looking to develop such floor interfaces.

Design Dimensions of History-enriched Floor Interfaces Based on these findings, a set of design dimensions that can help designers in the design of history-enriched floor interfaces are presented below:

Information sources: These are the various sources of information that can be displayed and/or encoded in the navigational traces. These include information about individuals such as user ID, movement direction, age, gender, interests, likes, familiarity level and group size. User ID and direction should always be displayed to support navigation. adding additional sources should be done carefully without overwhelming users with too much information.

Information encoding: This dimension explains how each of the presented information can be encoded. Approaches to encode information can be by using different footprints colours, sizes, patterns or user-defined shapes. For example, user ID and age can be encoded using colour and size respectively.

Representation: Navigational traces can be represented by showing individual footprints of each user (e.g. encoding user IDs using colour) or by using an aggregated representation that represents the average activity of users. Designers can use a single technique for the representation or employ a mixture of the two techniques as explained earlier.

Limitations One limitation arises from the background of participants in both studies. Participants recruited did not have a design background and were mainly engineering staff and students. It is possible that this have affected the generation of visualisations in Study 1 and hence the experiences and decisions of the following study. Also, the demographics of the recruited participants (i.e. background and occupation) limit the generalisability of the findings.

4.5 Conclusion

In this chapter, I presented two studies: Study 1 examined how social cues can be visualised, how they impact navigation decisions when presented on the floor and how they are interpreted, Study 2 engaged future users in designing for the challenges identified in Study 1 while using an interactive floor interface as a probe. Findings from Study 1 showed that direct and intuitive visualisations (i.e. footprints) are well-suited to represent traces of other people. Also, I identified a number of challenges in the design of floor interfaces that show social cues including, how to represent multiple people in the same space and how to design more prominent visualisations. From the design sessions in Study 2 , I gained insights into designing floor interfaces that influence and nudge navigation decisions. I showed that using realistic visualisations of in the design of such floor interfaces is preferred. In the next chapter, I examine the impact of the designed floor interfaces, which utilise the Social Norms mechanism, on navigation decisions.

CHAPTER 5

Evaluating the Effect of the Social Cues on Navigation Decisions

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THIS CHAPTER:

- Presents a lab-based study that investigates how the designed social norms nudge and the social cues it employs, which are presented as footprints on an interactive floor interface, impact navigation decisions.
- Describes how path choice behaviour is influenced by the presence (intervention) and the absence (control) of the social cues in two task-based scenarios: exploration and search.
- Shows that the social cues has an effect on path choices depending on how participants in the intervention condition interpreted them.

I have published the study presented in this chapter in [C.2].

5.1 Introduction

Findings from Chapter 4 showed that ambient technologies in the form of floor interfaces can be designed using the social norms nudging mechanism to present social cues that nudge and influence people's navigational decision-making. However, the impact of such social cues, displayed as footprints on an interactive floor display, on path choice behaviour has not been examined yet. Although previous work [207] showed how floor interfaces can act as an ambient display for social awareness as well as an interactive display for fostering engagement among users by augmenting the physical environment with digital traces of walking patterns, their work does not explore empirically the impact of such digital traces on navigation decisions.

Therefore, in this chapter, I examine the influence of the designed social cues on navigation decisions. I conduct a lab-based study that examines and compares path choice behaviour in the cases of presence (intervention condition) and absence (control condition) of the social cues. The floor interface, which was used in Chapter 4 during the design sessions is used during both conditions in two task-based scenarios: exploration and search. I collect quantitative and qualitative data to gain an in-depth understanding of participants' choices and interpretations. The chapter ends with a discussion of the influence of nudging using social cues on path choice behaviour.

5.2 Method

The objective of this study is to investigate whether and how the social norms nudge and the social cues it uses, which are presented as footprints on a floor interface, influence path choice behaviour. In particular, the study examines the following sub-questions in more depth:

- How do digital social cues affect path choices?
- How do digital social cues affect decision-making behaviours?
- How do participants interpret the digital social cues in the given navigation scenario?
- How do participants interact with the floor display in the given navigation scenario?

An interactive floor display (developed in Chapter 4) was used to examine and compare participants' behaviours in control and intervention conditions during free exploration of the space followed by search. Ethics approval was obtained from the university's ethics committee before carrying out the study.

5.2.1 Participants

Twenty-four participants (11 female), aged between 18-30 years (M = 21.8 years old, SD = 2.4), were recruited from my university. The mean age of the control condition (5 female, 7 male) is 22.4 years old (SD = 2.7). The mean age of the intervention condition (6 female, 6 male) is 21.2 years old (SD = 2.0). Participants were a mix of university students (undergraduate and postgraduate) and academic staff. They were recruited via advertising emails and by posting flyers in my university building. All participants have attended at least one poster session in a different location during the last year. They were unfamiliar with the study space. They were compensated with a £5 voucher.

5.2.2 Choice of Study Environment

Investigating the influence of nudging using social cues, which are shown in an interactive floor display, on path choice behaviour through a controlled yet ecologically valid study is challenging. Research into public and ambient displays recognises the challenges in conducting experimental studies in the field [8, 126]. Whilst conducting experimental research in the field offers great opportunities to examine the influence and interactions in ecologically valid conditions, it can be difficult to achieve as we lose control over factors and risk introducing confounding variables. Many studies that investigate the influence of floor visualisations on spatial behaviour have conducted laboratory studies to gain more control over variables [106, 176, 182]. Thus, the influence of social cues on path choice behaviour was addressed in a laboratory setting that offers more control over the intervening variables as well as enables interactions with the floor interface.

5.2.3 Experimental Design

A between-subject design was used, with one independent variable; the presence/absence of social cues. Therefore, the conditions examined are: *control*, in which social cues were not present, and *intervention*, in which social cues were present. In 50% of the intervention condition cases (6 participants), the cues were shown on the left path choice, whereas in the other 50% of cases (6 participants), social cues were shown on the right path choice.

5.2.4 Task

The influence of social cues on path choice behaviour was evaluated in two steps: free exploration of the space followed by a goal-directed search task. Since these two task steps are fundamentally different in their execution and the decision-making processes they rely on [332], this study does not conduct any comparisons between them (and are hence not a within condition). The context of the task was a poster session at a conference. In the free exploration step, participants were given a task-based scenario and were asked to *Explore* the space freely and have an overview of the posters without time limitation. In the search step, participants were given another scenario and were asked to *Search* for information in the poster, with a given code, in a limited time. These two scenarios can be found in Appendix C.1. Codes were added at the bottom of each poster which were hidden during the free exploration step. Participants were given a card showing the poster code and a pen to write the required information.

The aim of exploration tasks is to develop survey knowledge and gain spatial understanding [79]. Therefore, in order for participants to gain an understanding of the unfamiliar environment and explore it (since none of the them have visited the space before), the study started with the *Explore* followed by *Search*. This is a common approach in prior wayfinding and navigation studies [111, 232], which tend to start with the free exploration of the space first to familiarise participants with the environment. In addition, starting the *Explore* after the *Search* would negatively affect the nature of the task and the logical sequence of carrying it. It was expected that the task occurring in the first step would always affect the results of the task happening in the second step as people tend to depend heavily on prior experiences to navigate environments [133, 186].

In our daily life, we usually explore environments without time constraints. Search, on the other hand, can occur with or without time constraints (e.g. searching for a room in a building before a meeting starts or searching for an item in a supermarket when you have no other commitments after the trip). A time limit was added to evaluate this particular type of search. Adding time limit affects the decision-making process and increases task difficulty by introducing the stress factor [192, 193, 199, 291], and the study aims to examine the technology in that particular context. In addition, research has shown that search behaviour is influenced by the degree of familiarity of the environment [332] and that people perform better in familiar environments compared to unfamiliar environments [108, 133]. Therefore, conducting search with time limit would address the effects of the familiarity of the space.

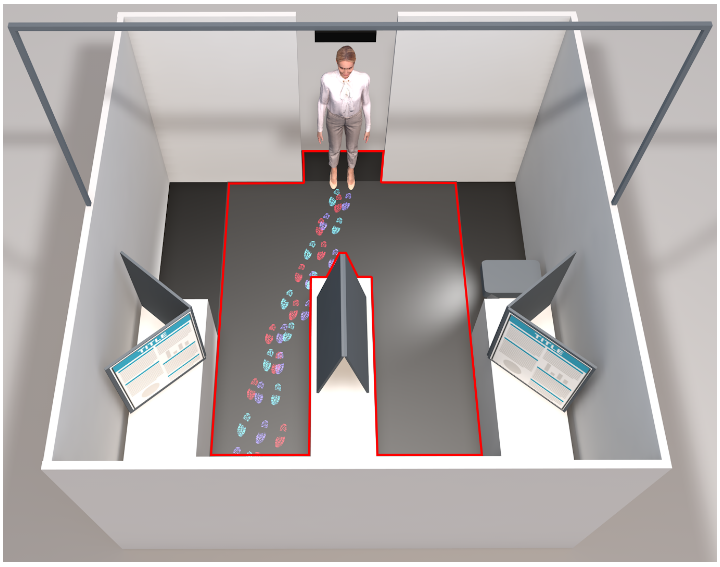


Figure 5.1: Experimental setup (tracking area in red).

5.2.5 Apparatus

The study space was 4.4m x 3.5m and offered two navigational choices for participants; left or right (See Figure 5.1). A Y-shaped environment that offers a binary choice was chosen because such environments facilitate the understanding of the complex decision-making process [342]. One poster was placed in each of the path choices. Posters were facing the back of the room so that a participant standing at the starting point would not be able to read their content. This ensures that participants' navigation decisions were not affected by the content of the posters.

The same study space was used for *Explore* and *Search*.

The same interactive floor system, which tracks users' movements and projects their footprints on the floor, that was implemented and used in Chapter 4 is used in this study. Users can interact with the floor system actively (e.g. creating drawings with their footprints), passively (e.g. gazing their footprints) or implicitly (e.g. ignoring the interactive floor).

The floor system consists of a Microsoft Kinect camera and a short-throw projector (BenQ MW864UST, running at 1920x1080p resolution). Two different views of the system were implemented, depending on the experimental condition. In the control condition, the system only tracks and projects the footprints of the participant when she moves in the study space. In the intervention condition, the system shows predefined social cues of three people in one of the path choices (i.e. left or right, 50% chance) in addition to tracking and projecting the participant's own footprints. Different settings were tested to determine the number of the predefined social cues. To indicate that a number of people took a particular direction using the predefined social cues, I started to examine social cues of 3, 5 and 7 people. After several tests, representing 3 people using the predefined social cues was chosen because representing more than 3 people created too much clutter and made the content unclear in the given study space. Prior work [207] has also noted that too many navigation traces on the floor made it hard to understand the floor visualisation. A different colour for each of the predefined social cues was chosen. The participant's own footprints were coloured in a different colour. The footprint visualisation was selected in this study as Chapter 4 demonstrated that it offers an intuitive and simple representation of human movement patterns.

5.2.6 Procedure

Participants were given an overview of the study, explaining the space area and the task. Then, they completed the consent form and demographics questionnaire. They were then assigned randomly to the control or intervention conditions. To start the *Explore*, they were asked to stand at the starting point, which is located outside of the study space. The researcher read the scenario while the participant was standing at the starting point. Participants were instructed to start immediately after the scenario and to return to the same starting point after completing the task. *Search* started after completing the *Explore*. The researcher revealed the poster codes, which were at the bottom of each poster, between the tasks while the participant was waiting outside of the study space. The same instructions were given to participants in the *Search* task. After completing the task, participants were interviewed and asked questions about the tasks, their choices, interpretations and the use of the floor display (See Appendix C.2). On average, the experiment took 35 minutes per participant.

5.2.7 Data Collection and Analysis

The performance of participants was video-recorded, observed and notes were taken. Semi-structured interviews were conducted after completing the task. The interviews were audio-recorded.

5.2.7.1 Task Completion Time:

Task completion time was measured in both the Explore and Search from the moment the participant leaves the starting point until they return to the same point after completing the task.

5.2.7.2 Analysis of Path Choices:

Fisher's exact test on *Explore* and *Search* was performed to compare the effect of nudging using social cues on path choices between the control and intervention conditions. Fisher's exact test is more accurate than Chi-Square test when the sample size is is less than 1000 [194]. The location of cues in the intervention condition was randomised with an equal number of left and right cues. Hence, in this analysis, the social cue location variable was divided into three values: *No cue, Left cue, Right cue*. The other variable, path choice, had *Right* or *Left* values. Fisher's exact test determines whether the proportions of the cue location variable (No cue vs. Left cue vs. Right cue) is different depending on the value of the other variable (e.g. Right path choice).

5.2.7.3 Analysis of Qualitative Data:

All interviews were transcribed verbatim. Qualitative data collected from video observations and interviews were analysed using thematic analysis, where Braun and Clarke's six-phase framework [45] was followed. The first author read and openly coded the videos and interviews to generate the initial codebook. Peer validation [5] was conducted throughout the coding process with two additional researchers. The team of researchers met regularly to review and clarify codes and themes. An inductive approach was followed in which the categorisation process was driven by the data. NVivo, the qualitative data analysis software, was used to thematically analyse the data.

5.3 Results

5.3.1 Task Completion Time

Overall, participants spent an average of 173 seconds (*SD*=88.11s) to complete the *Explore* and an average of 30.43 seconds (*SD*=15.76s) in the *Search*. In the control condition, participants completed the *Explore* in an average of 166 seconds (*SD*=71.15s) and an average of 33.22 (*SD*=

22.62s) in the *Search*. Participants in the intervention condition completed the *Explore* in 179.72 seconds (*SD*= 105.06s) and the *Search* in 27.65 seconds (*SD*=8.90s).

5.3.2 Understanding the Effect of Digital Social Cues on Path Choices

To examine how digital social cues affect path choices, I start by first presenting the quantitative findings of path choices, followed by the qualitative results.

5.3.2.1 Quantitative Findings of Path Choices

Using Fisher's exact test, the effect of social cues on path choices between the control and intervention conditions was compared. these findings are presented for the *Explore* and *Search* tasks.

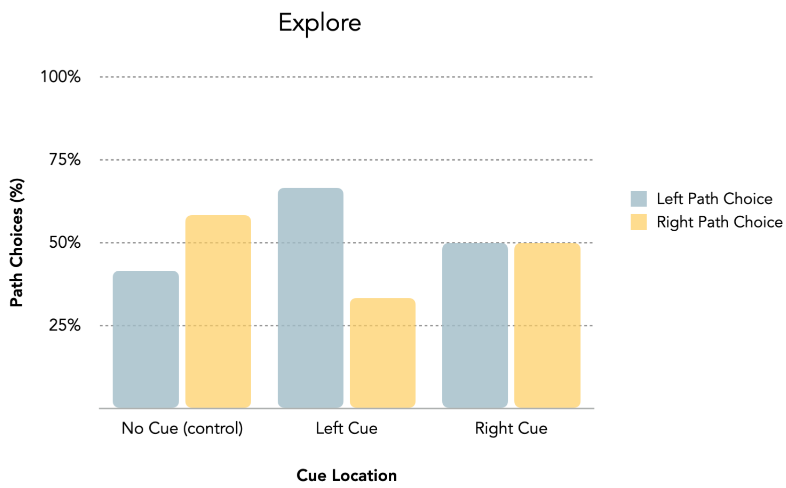


Figure 5.2: Path choices of participants in the control and intervention conditions during the *Explore*

Step 1 - Explore: Figure 5.2 shows that in the *Explore*, 58.3% of the participants in the control condition took the right choice whereas in the intervention condition, 33.3% who were shown the left cue chose the right path choice and half of the participants who were shown the right cue selected the right path choice. Fisher's exact test showed that the difference was non-significant.

Step 2 - Search: In the *Search* task, more than half (58.3%) of the participants in the control condition chose the right path choice while all of the participants in the intervention condition followed the social cues when they occurred on both left and right locations (See Figure 5.3). This difference was statistically significant (p=0.001, *Fisher's exact test*). Post-hoc tests were performed to identify which of the three pairs was significant. Three pairwise comparisons (no cue vs. left cue, no cue vs. right cue, left cue vs. right cue) tested using Fisher's exact test were carried out. Bonferroni-correction was applied to correct for the multiple comparisons and the

Bonferroni-adjusted p-value used was 0.017. Post-hoc tests showed a significant effect of the cue (left cue vs. right cue) on the participant's path choices in the *Search* task (p=0.002), i.e. all of the participants in the intervention condition selected the path that showed the cue. No evidence of significant differences was found in path choices between the control and intervention conditions (no cue vs. right cue and no cue vs. left cue) in the *Search* task.

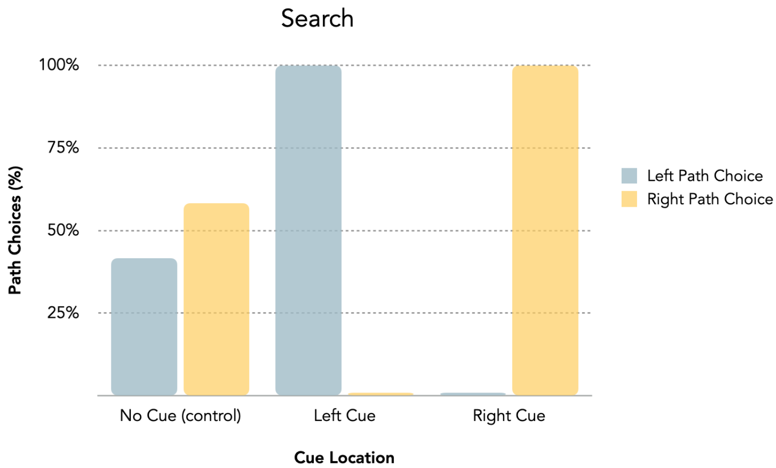


Figure 5.3: Path choices of participants in the control and intervention conditions during the *Search*

5.3.2.2 Qualitative Findings of Reasons Behind Path Choices

Using thematic analysis, the following themes were extracted from the interviews, which describe the factors that affected participants' path choices during the Explore and Search tasks in both conditions (control and intervention):

(1) Individual differences: 9 participants expressed the effect of personal factors such as handedness, cultural influences, habitual behaviours and preference on their path choice behaviour. For example, P1 reported that she is left handed and she approaches everything naturally towards the left. P21 and P9 pointed out how the cultural factors effects their choices: *"In china, we always prefer to walk on the left"* and *"to start in an orderly manner from left to right"*. P8 indicted that his choices reflect a preference towards one side. Other participants stated that their path choices are habitual behaviours *"I tend to go to the right-hand side first"(P11)*.

(2) Prior task experience. 11 participants highlighted the effect of the first task choice on the their choice in the second task. For example, participants reported repeating the choices they selected in the first task, e.g. *"I repeated my movement again " (P5)* and *"because it is the one I visited the first time " (P9)*. Participants also mentioned how the knowledge they gained from the first task have affected their choices. For instance, P22 reported that her choice was because the

"The poster was so fresh in my mind". P6 explained that she selected one path choice because she did not pay enough attention to it during the first task.

(3) Floor visualisation. 11 participants in the intervention condition highlighted the effect of the floor visualisation on their choices. For example, P24 found that the floor visualisation attracted them to take one of the path choices; *"I felt more drawn to that direction then the other one. I suppose if you got two decisions in front of you, you are going to go with the one that is more prominent"*, whereas some participants reported that they avoided paths because the floor visualisation gave the impression of crowds; e.g. *"I assumed more people on the right so I just went to the left" (P16), "I avoid the crowd" (P6)*. Some participants reported that the floor visualisation acted as a guide while selecting their path choices; e.g.*"I saw the footsteps on the floor, and I just followed the steps" (P12), "because the traces showed left" (P25)*.

(4) Difficulties in providing justifications. 8 participants had difficulties in explaining the reasons behind their choices. For example, they described their choices as *"random" (P1), "it was not a conscious decision" (P18), "no particular reason" (P21)*. Three participants justified their choices by linking them to actions performed and descriptions given by the researcher such as the way the researcher explained the study (although the researcher used the same general study description with all participants) and the movements that the researcher made while setting up the study.

5.3.3 Decision-making Behaviours

From the video observations, the way participants selected their path choices in the intervention and control conditions was examined and analysed in order to examine how social cues affect decision-making behaviours. The behaviours made by participants in order to reach their first destination were coded. Four main categories of behavioural patterns were identified:

(1) Direct movement towards the goal: In this category, participants determined their navigation choice early (i.e. as soon as they entered the study space). Participants moved directly to their first target without any shifts or stops. Some participants in this category moved slowly and checked their path as they walked towards the goal while others were faster and moved without checking their surroundings. Six participants in the control condition and seven participants in the intervention condition followed this pattern, as shown in Figure 5.4 (a).

(2) Deciding while moving: Participants in this category positioned themselves centrally as they entered the study space and shifted towards one of the directions without stopping after reaching the centre of the space. This pattern was observed in both the intervention (n=3) and control (n=2) conditions (see Figure 5.4 (b)).

(3) Stopping to decide: Participants located themselves at the centre of the entrance, moved until they reached the centre of the study space and stopped for some time to decide which path to take. This category was more evident in the control condition (n=3) where no social cues were provided than in the intervention condition (n=1) (Figure 5.4 (c)).

(4) Reconsidering decisions: Two participants started to take one of the path choices but changed their minds and shifted to the other path choice (Figure 5.4 (d)). The change was done at some point before reaching their first target. For example, one participant in the intervention condition shifted to the direction of the social cues but they changed their choice as soon as they realised they were following the footprints.

All of these behaviours were observed during the *Explore* when the time was unconstrained. During the *Search*, the observed patterns of all participants were direct movement towards the goal.

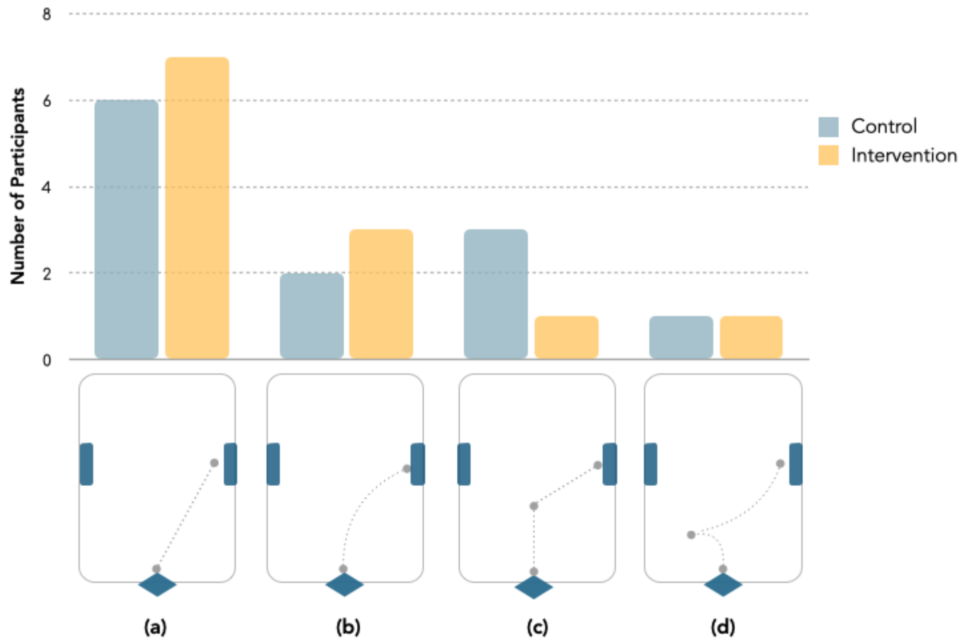


Figure 5.4: Decision-making Behaviours in the control and intervention conditions during the *Explore* step: (a) Direct movement towards the goal (b) Deciding while moving (c) Stopping to decide (d) Reconsidering decisions

5.3.4 Interpretation of digital social cues

The interviews were analysed to understand how people interpret the digital social cues. Using thematic analysis, two main themes were identified: Symbolic information and Social information.

(1) Symbolic information (n=5): A number of participants expressed that the cues represented an abstract representation of direction. Participants stated that the visualisation proposed a direction to take, e.g. *"the suggested path to take "(P4),"indication that I should go left" (P25)*, whereas P26 noted that the visualisation acted as a navigational aid: *"it guides you towards a poster"*. P20 pointed out that he would avoid this type of directional aids in public spaces and that explains his path choice behaviour during the study. Four out of five participants who interpreted

it using symbolic interpretation followed the social cues whereas one participant preferred to avoid them in the *Explore*. All of these participants followed the cues during the *Search* as shown earlier.

(2) Social information (n=9): Several participants reported extracting social information from the cues such as awareness of other people, their behaviours and activity levels. For example, participants highlighted that the social cues represented social presence; e.g. *"general traffic" (P8),"tracks of people" (P6)*. P6 and P18 stated that the cues showed the behaviours and choices made by other people; *"It seems like what a lot of people do" (P18),"people who have gone there" (P6)*. P14 highlighted that the popularity of space areas can be assessed by knowing the movement patterns on the floor visualisation. Participants also pointed out that the cues helped in retrieving information about the activity level in the path;*"lots of footprints going that way, which means that direction is busy" (P22)*. Five participants who interpreted them as social information followed the social cues and four participants avoided the cues during the *Explore* while all participants followed the cues during the *Search*.

5.3.5 Floor Interactions

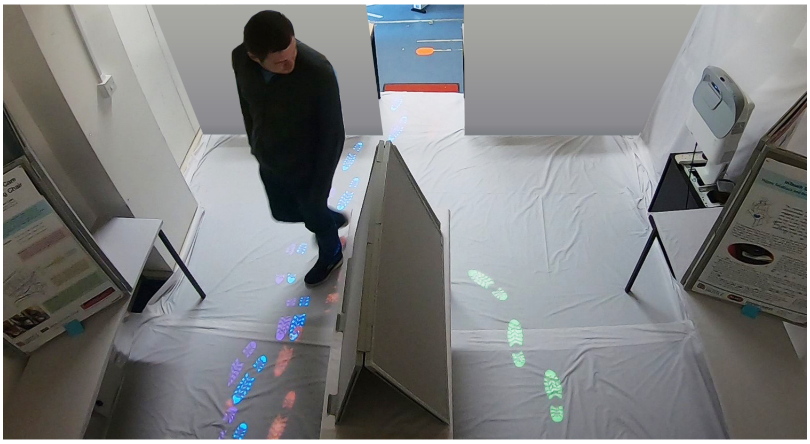
To examine how participants interact with the floor display, video recordings were analysed. This resulted in coding 48 interaction instances with the system during the *Explore* and *Search*. An interaction instance was collected every time a participant enters the study area, hence two instances were collected for each participant (one for each of the *Explore* and *Search*). The interaction modes proposed in [207] were used to extract the ways in which people interacted with the system during the task. Two ways of interaction were identified, as shown in Figure 5.5:

(1) Passive engagement (25%): Occurred when participants noticed and gazed at the floor to look at the footprints they created while completing the task. Within each interaction instance, most participants gazed at the floor once or twice, only two participants observed the floor more than twice. This type of interaction was more evident during the *Explore*.

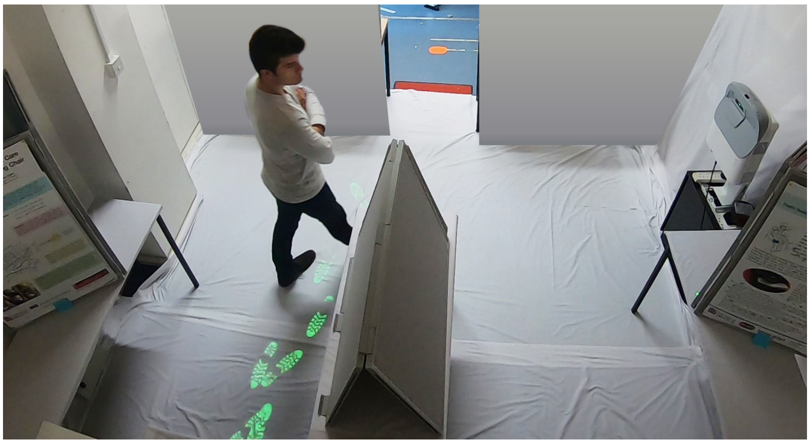
(2) Implicit interaction (75%): Occurred when participants did not look at the floor during the tasks either because they were unaware of or ignored the interactive floor. This type of interaction was apparent during the *Search*.

5.4 Discussion

Social cues in the form of activities performed in the past (e.g. physical traces) influence navigation decisions [77]. Recent advances in interactive floor interfaces have allowed augmenting spaces with digital traces [207]. However, employing such social cues to influence and nudge navigational decision-making as well as examining their impact on navigation decisions have not yet been empirically examined. This study examines how the social norms nudge and the social cues it employs influence navigation decisions.



(a) Passive engagement.



(b) Implicit interaction.

Figure 5.5: Observed floor interactions during the tasks showing in (a) passive engagement and in (b) implicit interaction

While the quantitative findings showed no evidence that digital social cues can influence and nudge path choice behaviour during the *Explore*, the qualitative results showed that path choices of all participants, except one, were influenced by the social cues. These findings showed that participants made their path choices based on how they interpreted the cues. For instance, some participants preferred to follow popular paths, whereas others preferred to avoid paths that are *busy and crowded* and take unexplored paths. This suggests that the influence of the social cues is not necessarily limited to attraction and nudging towards the path but it can also deter people from taking certain paths during exploratory tasks. It is essential for researchers and designers to consider both types of understandings and uses when using such floor interfaces with social cues to nudge and guide people towards certain direction.

It was expected that the social cues would not influence participants' path choices during the *Search*. Although all participants in the intervention condition selected path choices with social cues in the search task, this result was not significant compared to the control. Interestingly, by examining the intervention condition alone during the *Search*, the results showed a strong effect of digital social cues on path choices. This suggests that the effect of such cues can be powerful in time-constrained cases. It is possible that participants considered them a key to their search. Prior work [78, 340] have shown that, in natural environments, people use social cues during exploratory tasks, further research is needed to understand how they are used during search tasks.

Although all of the decision-making behaviours in the *Explore* occurred in both the intervention and control conditions, a pattern of behaviours in each of these conditions was observed. In particular, participants in the intervention condition showed more direct behaviours and less hesitation and stops, whereas the participants in the control condition showed less direct behaviours and more hesitation. This suggests that social cues can, to a certain extent, influence and nudge decision-making processes while exploring spaces. Thus, their use in public spaces could facilitate and nudge individuals while making navigation decisions in unfamiliar environments. As expected, regardless of the experimental condition, only one behaviour type was found during the time-constrained search. This shows that participants (in both conditions) during such search tasks do not face the problem found during exploration. The decision-making process was faster due to the requirements of the task. Together, these findings suggest that when exploring spaces freely, more time is spent on assessing the various environmental variables (which resulted in the four types of decision-making behaviours) in order to select one of the path choices. This aligns with prior work on exploratory tasks [340]. However, less attention would be paid to these variables when searching for information in a limited time.

The given context of the study scenario resulted in social and symbolic interpretations of the social cues. It is possible that the symbolic interpretation have emerged due to linking them to the static navigation aids that are usually used within buildings to direct people to certain areas. It is also possible that symbolic interpretations arise when users are unaware of their interactions with the system. This points towards the recommendation that designers need to foster the social interpretation of the cues by applying extra measures to limit the symbolic interpretations. For example, systems can incorporate additional features that explicitly inform users about their interactions with the system (e.g. audio feedback) or can use visualisations that show different sole sizes of the footprints.

Although it was predicted that participants would actively engage and interact with the display (e.g. creating drawings with their footprints) during the *Explore*, the data showed no active engagement with the floor display. Prior work [207] have found that active engagement with a floor display situated in an open space represents only 7% of all the observed interaction instances. It is possible that the controlled study space and the study requirements had an effect on the range of interactions. As shown in the literature [177, 207], it is expected that using floor displays in open spaces would involve, to a certain extent, active engagement with the system.

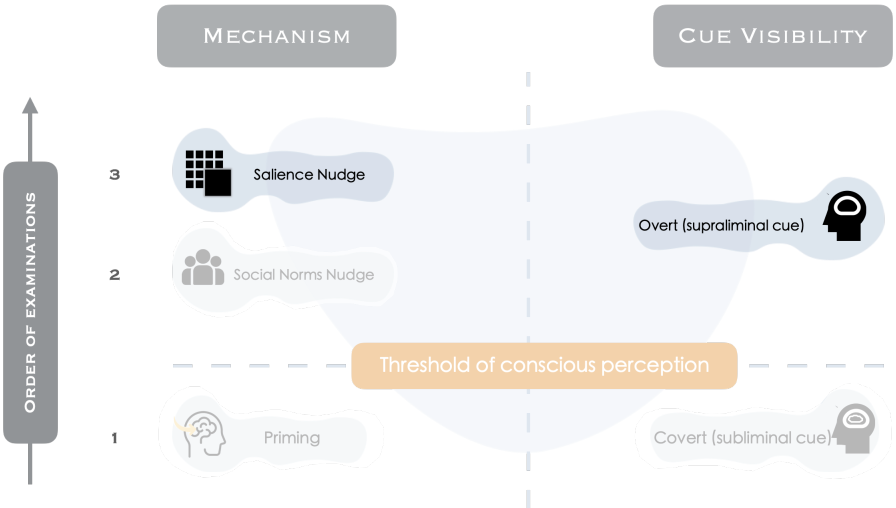
Limitations One limitation arises from the exchange of ecological validity for experimental control. By conducting the study in a controlled environment, we control for confounding variables but this limits our understanding of the effect of digital social cues in ecologically valid conditions. In addition, the design space for designing the intervention condition in this study is vast. Additional limitation of this study arises from examining a single intervention condition (i.e. digital social cues in one form). Possible variations include exploring animated footprints as well as physical footprints. Examining this design space would provide further understanding of the impact of the digital social cues on spatial behaviour. Another limitation of this study is the number of participants examined. It is possible that the quantitative results were affected by the number of participants. Finally, the findings are limited to examining path choice behaviour of individuals. People's spatial decisions in public spaces are influenced by their companions [324], it thus remains unclear how group size would impact the effectiveness of these cues.

5.5 Conclusion

In this chapter, I investigated the influence of the designed Social Norms nudge and the social cues it employs, on navigational decision-making. In a lab study, I examined the impact of social cues, presented as footprints on a floor interface, on navigation decisions in two cases: presence (intervention condition) and absence (control condition) of the social cues. I gained novel understanding into the influence of such social cues on navigation decisions. I demonstrated that the influence of social cues on navigation decisions depends on how the cues are interpreted. In the next chapter, I examine a different nudging mechanism, i.e. salience mechanism and explore a different type of supraliminal cues; physical cues. In particular, I examine how physical cues of shape-changing walls can be designed to influence navigation decisions while being ambient and minimally-intrusive.

CHAPTER 6 & CHAPTER 7

Salience Mechanism with Supraliminal Cues



CHAPTER 6

Understanding & Designing Physical Cues of Shape-Changing Walls

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THIS CHAPTER:

- Presents an online study in VR examining how people experience different types of shape-changing walls in VR.
- Describes how physical cues of shape-changing walls can be designed, using the salience nudging mechanism, to nudge and influence navigation decisions without being intrusive by engaging potential users in the design process.
- Provides novel insights into how people perceive large-scale shape-changing walls in VR and how these walls can be designed to subtly influence navigation decisions within the built environment.

6.1 Introduction

In Chapter 4 and Chapter 5, I explored one way of influencing decision-making using supraliminal cues (i.e. a higher cue level compared to subliminal cues examined in Chapter 3), which was delivered through the social norms nudging mechanism. Another cognitive bias that people employ to aid them in making navigational decisions while exploring novel environments is the salience bias [250, 317–319]. With this bias, people are more likely to attend to items or information that are prominent and ignore those that are less noticeable at the critical moment of decision-making [154]. Saliency arises from contrast between elements and their surroundings (e.g. a red dot in a group of black dots) [153, 166, 219]. The contrast can be expressed in terms of perceptual qualities such as size, colour, shape, pattern, texture, light or movement [48, 251]. These attractive features create a bottom-up attentional capture that affects people's navigational decision-making [35, 48].

One promising technology that can be used with the salience nudging mechanism is shape-changing interfaces. The movement and shape change qualities of such interfaces make them salient and attention-grabbing when embedded in our everyday environments. Thus far, there exists a number of shape-changing interfaces including, small-scale interfaces such as devices (e.g. [162, 253]) as well as large-scale interfaces such as shape-changing ambient sculptures (e.g. [142, 251]) and shape-changing walls (e.g. [114, 271]). In particular, shape-changing walls can be appropriate for nudging and influencing people's navigational decision-making using the salience nudging mechanism. This is because of their qualities that make them prominent, which would cause salience bias in people. Also, because shape-changing walls are an architectural element that allow them to blend with the surrounding environment and become ambient (i.e. can move back and forth between centre of attention and periphery) depending on their design.

However, designing shape-changing walls to nudge and influence navigation decisions (by exploiting the salience bias) has not been explored yet. In addition, our understanding of how shape-changing walls can be designed to become ambient and move to the periphery of our attention when not needed remains limited, thus, it is essential to examine how they can be designed to influence navigational decision-making with minimal intrusiveness levels in order to blend with the environment. To examine the design of such shape-changing interfaces, prior work have paved the way by proposing the use of platforms that do not require building prototypes such as 2D videos [228] and Projected Augmented Reality [50]. In this work, I propose the use of Virtual Reality, which could offer more immersive experiences that would allow examining how different designs of shape-changing walls affect people's experiences and navigational decision-making.

In this chapter, I use Virtual Reality (VR) to examine how shape-changing walls can be designed with the salience nudging mechanism to influence and nudge navigation decisions. VR can be a powerful tool for prototyping complex technologies, examining a wide range of possible designs and studying user behaviour [110, 211, 339]. In particular, I use mobile VR[1] to study the design of shape-changing walls as it offers immersive experiences that are accessible to all smartphone users. To examine their design, I conduct a study consisting of three parts: 1) VR experience: this part aims to understand how different designs of shape-changing walls affect users by obtaining initial impressions and emotional reactions when experiencing shape-changing walls in VR ; 2) Co-design activities: this part investigates the design of these shape-changing walls by inviting potential users to participate in the design process. The co-design activities particularly examine designing shape-changing walls with ambient qualities (i.e. non-intrusive)

[1]Mobile VR was used to avoid any contact with participants during the COVID-19 pandemic

as well as designing them to nudge, influence and guide navigation decisions. 3) Interview: this part asks participants to reflect on the VR experience and the overall design process. The chapter concludes with a discussion of the findings.

6.2 Background

6.2.1 Spatial Skills in Real-world and Virtual Environments

Lohman et al. [180] defines spatial skill as the human's ability to generate, retain, remember and alter visual images. Spatial orientation skill, which is a sub domain of spatial skills, refers to the individual's ability to understand spatial relations between objects and space [53]. Prior research has shown that spatial skills can transfer between real and virtual spatial experiences since the same neural networks are involved in processing spatial information(e.g. [140, 210]). For instance, Kinateder et al. [164] demonstrated that in a crowded and stressful virtual situation, people behaved in ways similar to a real-world situation. Although general spatial information can transfer between real-world and virtual environments, there are a number of limitations of the virtual experience [64]. For example, in a virtual environment, the use of information is less flexible compared to a real environment. In addition, there are differences in the way people navigate these worlds. This occurs because the perceptual and proprioceptive feedback of the real-world experience can impact the way people navigate environments [64]. In particular, virtual environments have a limited field of view compared to real environments, which can negatively impact spatial behaviour and spatial knowledge acquisition [269, 325]. Furthermore, gaze behaviour in virtual environments is different compared to real environments, which can make knowledge transfer between real and virtual environments difficult [226].

6.2.2 Shape-changing Interfaces

Shape-changing interfaces use physical changes in shape or material as input and/or output [4]. Such interfaces can convey different types of content including, information or emotions. They are interactive with self and/or user actuation capabilities [4]. Shape changing interfaces have been used for various purposes including, functional purposes such as information communication, dynamic affordances (i.e. communication of possibilities for action), simulation as well as symbolic purposes such as aesthetics and fun [4, 243].

Several taxonomies and models have been developed to identify and describe the various types of shape change. For example, Coelho et al. [66] presented a taxonomy that focused on the technological properties of shape-changing interfaces such as power requirements, speed and resolution, number of memory shapes, trainability and reversibility. Following a review of existing work on shape-changing interfaces, Rasmussen et al. [243] identified eight different types of shape change including, Orientation, Form, Volume, Texture, Viscosity, Spatiality, Adding/Subtracting, and Permeability. Roudaut et al. [253] introduced the term shape resolution that is based on the

Non-Uniform Rational B-splines (NURBS) and has ten features including, Area, Granularity, Porosity, Curvature, Amplitude, Zero-crossing, Closure, Stretchability, Strength and Speed. A refinement of this taxonomy included two new features Size (with three sub-features: Length, Area and Volume) and Modularity [161]. Sturdee et al. [288] reviewed existing shape-changing interfaces prototypes and proposed a categorisation of them that includes Enhanced 2D, Bendables, Cloths and Papers, Elastics and Inflatables , Actuated , Liquids , Malleables and Hybrids. These models and taxonomies support researchers and practitioners in understanding the design space of shape-changing interfaces and help in informing the design of future interfaces.

6.2.3 Large-Scale Shape-Changing Interfaces

Although the majority of the existing shape-changing interfaces are considered small-scale interfaces such as devices (e.g. [162, 253]) and objects (e.g. [299]), there exists few shape-changing interfaces that are large-scale such as furniture, sculptures and architectural elements (e.g. wall, floor). For example, Takashima et al. [292] and Gronbaek et al. [118] proposed shape-changing tables that can dynamically deform into different shapes and positions for content visualisation during meetings as well as dynamic management of social interactions. Coelho et al. [65] presented Shutters, a shape-changing sculpture that is composed of a number of 3.5 cm X 3.5 cm shutters actuated using shape-memory alloys (SMA). These shutters can be individually adjusted and used for various purposes such as controlling ventilation, filtering lighting and presenting non-obtrusive ambient information. Also, Murmur [257] is a shape-changing sculpture that utilises the qualities of ambient displays. It is made of one hundred computer CPU fans that gets triggered by environmental sound. In addition to sculptures, shape-changing interfaces have extended to architectural elements such as walls and floors. For instance, Aegis Hyposurface [114] is a 10 m x 3 m shape-changing wall that is made of pneumatically-controlled metal plates. The wall deforms in real-time in reaction to environmental stimuli such as movement, sound or light. Another shape-changing wall was designed and used in the breathing room [271], which synchronises the individual's breathing pattern with the shape-changing wall. The wall consists of CNC cut wooden panels that deform in three dimensions. Furthermore, Suzuki et al. [290] and Teng et al. [296] explored shape-changing floors and presented pneumatically-controlled shape-changing tiles that can be used for adaptive furniture, information presentation and haptic interfaces for VR experiences.

6.2.4 Trade-off Between Building Shape-Changing Interfaces and Using Design Platforms

While the aforementioned large-scale shape-changing interfaces can offer great opportunities for enhancing people's experiences within buildings, designing them can be extremely challenging. This is because technologies needed to build such large-scale shape-changing interfaces are not fully ready yet, which in turn results in high development costs. To address these design challenges, researchers have examined the use of various design platforms including, 2D video [228] and Mixed Reality [50]. For example, Pedersen et al. [228] produced 51 videos of a shape-changing handheld device by varying shape-change parameters and examined how users perceive them. They showed that their approach (i.e. using video clips) can be feasible at capturing some of how users would perceive physical devices. Additionally, Cano et al. [50] used Projected Augmented Reality (AR) to examine the perceived affordances of seven visual effects of a shape-changing object. They demonstrated that Projected AR can be a promising platform to study shape-changing objects. Although Projected AR is feasible for designing small-scale shape-changing interfaces, it can be cumbersome to implement for large-scale interfaces as it would require additional projectors and accurate head tracking systems. Virtual Reality, on the other hand, can be a promising platform for designing large-scale shape-changing interfaces as it provides immersive and engaging experiences and enables users to interact with large-scale interfaces in a 3D world, which would allow the exploration and understanding of how such interfaces affect users' perceptions and experiences.

6.2.5 Designing in and for Virtual Reality

Virtual Reality (VR) allows users to immersively experience a virtual world [29]. VR has shown a promising potential in various application domains such as education, healthcare and design. In the design domain, researchers have used VR as a design tool for designing interactive spaces [148], products such as cars [343] and cakes [198], architecture and interior design [241] and as a design tool for speculative design and design fiction [195]. For example, Jetter et al. [148] explored the opportunities and challenges of designing (sketching and simulation) interactive spaces within VR. They showed that using VR as a design tool allows users to experience space in relation to their own body and supports playful design explorations. However, they found that VR design tools that would fulfil all designers' needs are limited and complex to build. In addition, Mei et al. [198] used VR as a tool for customers to co-design cakes with a chef, enabling users to visualise 3D virtual cakes and interact with them in real-time. They demonstrated that VR is well-suited for providing users with an immersive co-designing experience of cakes. McVeigh-Schultz et al. [195] explored placing design fiction explorations in VR for creative work and collaboration and referred to it as 'immersive design fiction'. They showed that this approach is suitable for prototyping embodied aspects of speculative experiences.

Furthermore, researchers used participatory design and co-design approaches to design VR scenarios in applications such exposure therapy [99], integration of VR into informal learning contexts [321] and examining social VR for older adults [21]. For instance, Flobak et al. [99] carried out a participatory workshop with adolescents to design VR scenarios for situations where a person may experience a fear of public speaking. The design process involved iterative stages of ideation, stoyboarding, live-action plays captured via a 360° video camera and experience-based evaluation. They demonstrated that this approach is ideal for designing realistic VR scenarios.

Vishwanath et al. [321] followed a similar approach to examine the incorporation of VR into informal learning environments. Through different co-design activities, students and teachers participated in designing VR scenarios for building social awareness. They showed that their approach helps in understanding the challenges and opportunities of using low-cost mobile VR for content generation in informal learning settings. While several research works have been conducted to design in and for Virtual Reality, it remains unclear whether and how Virtual Reality can be used to inspire and support the design of large-scale shape-changing interfaces.

6.3 Method

The study is designed to answer the following research questions:

- RQ1: How do people perceive different types of shape-changing walls?
- RQ2: How can shape-changing walls be designed to nudge navigational decision-making with minimal intrusiveness levels?
  - RQ2.1: Which shape-changing wall parameters affect the intrusiveness level of the shape-changing walls designs?
  - RQ2.2: How can shape-changing walls be designed to influence navigation decisions and nudge people toward certain directions within indoor settings?
- RQ3: Can VR be used as a platform to inspire and facilitate the design process of large-scale shape-changing interfaces?

To answer the raised research question, I conducted an online study with 18 participants. The study consists of three main successive parts: VR experience, co-design activities and an interview, as shown in Figure 6.1. The VR experience answers RQ1 by gathering first impressions and reactions of how shape-changing walls affect people's perceptions. Co-design activities answer RQ2 by engaging potential users in the design process of shape-changing walls in two design aspects: factors affecting intrusiveness of designs (RQ2.1) and designing to influence and nudge navigation (RQ2.2). I carried out these individual co-design sessions because one-to-one sessions allow capturing comprehensive data of the participants' unique experiences and co-design allows for generating innovative and creative ideas for complex problems [283]. Finally, the interview answers RQ3 by collecting reflections and feedback from participants about the overall process. Ethical approval for the study was granted by the university's ethics committee.

6.3.1 Participants

A total of 18 participants (9 female) took part in the study, with ages ranging from 23 to 57 years old (mean age = 32.66, SD = 8.7). To recruit participants, a digital recruitment poster/leaflet

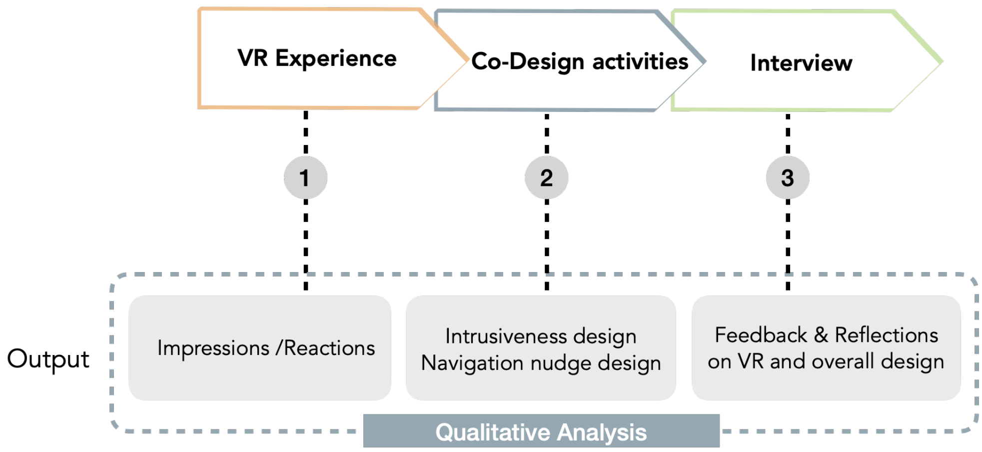

Figure 6.1: Overview of the steps followed to answer the raised research questions.

was shared with my network and posted on participants' recruitment websites and on social media platforms. Participants were a mix of students, academics and technical staff. Concerning their VR experience, three participants reported that they have not used VR before. Twelve participants who reported that they have used VR before considered their experience level with VR as beginners and three participants reported to be experts. Seven participants reported that they have no design experience while eleven participants mentioned that they have experience in design. Among the participants who possess design experience, two participants had a design experience of less than a year, one participant had an experience of 1-2 years, three participants had an experience of 3-5 years and five participants reported to have more than 5 years of design experience. Fourteen participants were android users and four were iOS users. Participants received a cardboard Virtual Reality Viewer (Figure 6.2) as a compensation for their participation and to use during the first phase of the study.

6.3.2 Parameters of Shape-Change Studied & Manipulated

Among the available frameworks of shape-change (described in Section 6.2), the framework of Roudaut et al. [253] is the most suitable for flat surfaces such as shape-changing walls. Therefore, I mainly used the features of this framework in this work. Out of the ten features, the following six were used: *Curvature*, *Amplitude*, *Zero-Crossing*, *Porosity*, *Granularity* and *Speed*. *Area* was substituted with *Volume* which is a part of the *Size* feature in a refined framework [161] of Roudaut et al.'s framework [253]. This is because of the three dimensional changes that it offers compared to two dimensional changes, which would be difficult to view in a room setting of four intersecting walls. Three features were eliminated including, *Stretchability*, *Strength* and *Closure*. *Stretchability* and *Strength* are tactile features, which do not apply to shape-changing walls. *Closure* is not applicable to walls and similar effects can be achieved by using the *Curvature* feature when the walls curve to a certain degree. Here, I define these types of change and describe the other parameters used in the study.

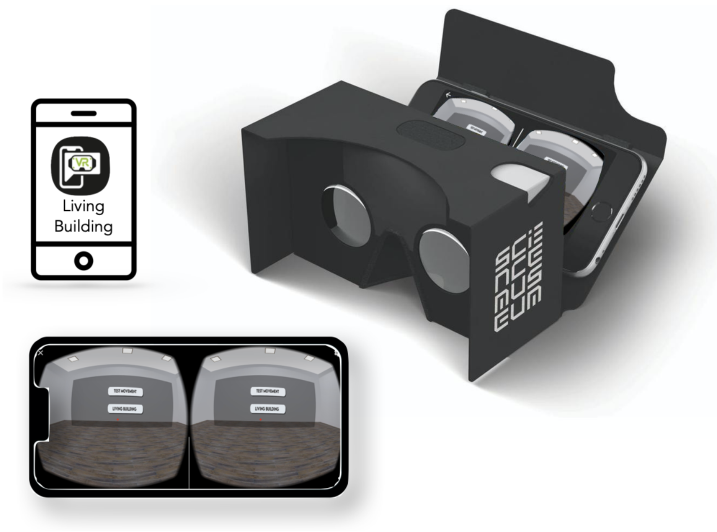

Figure 6.2: VR cardboard viewer used in the study and the home page of the Living Building mobile app showing Test Movement and Living Building buttons.

Type of Change This parameter corresponds to the type of change that can be used in the shape-changing walls. The used types of change are explained below:

- *Curvature* corresponds to the ability of an interface to alter the curviness of the surface. *Curvature* can be concave or convex.
- *Amplitude* describes the range of displacement of control points.
- *Volume* describes the volume of the object.
- *Zero-Crossing* explains the ability of a shape to have wave-like pattern.
- *Porosity* describes the ratio of the area of discontinuous parts to the total area of the shape.
- *Granularity* measures the density of physical actuation points.

Speed This parameter describes the time needed to move a shape from the initial rest state to its maximum state. I used four values for this parameter: slow, moderate, fast and variable.

In addition to the previous parameters, I added four more parameters: *Scale*, *Interaction*, *Notification Level* and *Abstraction Level*. I identified the *Scale* parameter because we needed a parameter to represent how large the change affecting the room is. Also, we needed a parameter to allow participants to describe how would they interact with the shape-changing walls during the design activities, hence I used the *Interaction* parameter from Rasmussen et al. [243]. In order to create designs for shape-changing walls that can become ambient and minimally intrusive, there is a need for parameters that describe such ambient technologies. Therefore, I used *Notification Level* and *Abstraction Level* parameters from Matthews et al. [191]

Scale This parameter describes the number of walls in a room that changes its shape. I used three values for this parameter: one wall, two walls and three walls (corresponds to all walls in the VR experience).

Interaction This parameter describes how a shape-changing interface uses shape change as input and output. The values of this parameter are:

- *No Interaction* means that shape change is used only as output and ignores any input from the user.
- *Indirect Interaction* means that shape change is used as output but the change is based on an implicit input (e.g. data collected without awareness).
- *Direct Interaction* means that the shape change is used as input and output. The user interacts directly with the system to change shapes and the change occurs as output.

Notification Level This parameter describes the degree at which the system notifies the user about the change in system state while performing another primary task [191, 300]. Notification level has five main levels: Ignore, Change Blind, Make Aware, Interrupt and Demand Action. *Ignore* corresponds to no notification. *Change Blind* corresponds to inattention,i.e. changes in the system state occurs but the user does not notice it. *Make Aware* uses a form of divided attention with noticeable changes in system state. *Interrupt* also uses divided attention, with attempts to attract user's focused attention. *Demand Action* requires the user to perform an action to stop the notification.

Abstraction Level This parameter describes the level of abstraction in the information presented by the interface, which is the process of removing data and including fewer details compared to the original design [191, 300]. Abstraction level can be *Low*, *Medium* or *High*. *Low* level represents data directly and without any abstraction. *Medium* level applies some abstraction to the represented data, while also keeping it comprehensible. *High* level encodes data strongly, with no relation to the real-world to enable comprehension.

In the study, I used simplified names for some of the types of shape-change. This is to make it easier for participants to remember the names of the types rather than using complex names that are difficult to recall. For instance, *Zero-Crossing* was replaced with *Waves*, *Amplitude* was replaced with *Cubes* and *Cones* depending on the shape used, *Porosity* was replaced with *Holes* and *Granularity* was replaced with *Number of Instances*. The names of the other types of change were not changed.

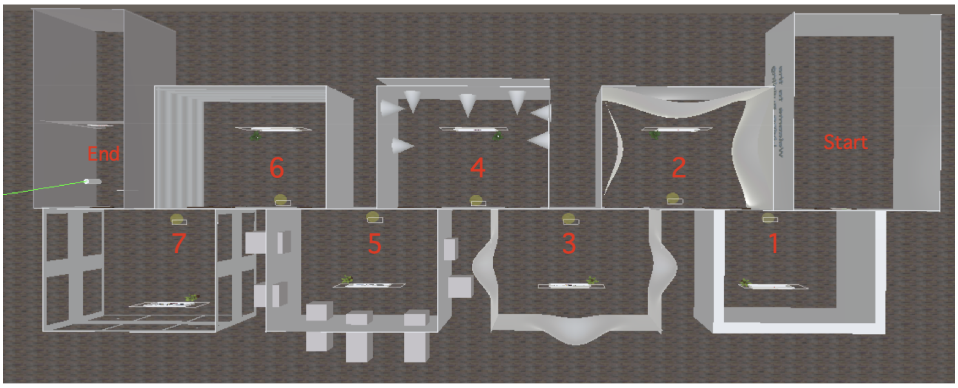

Figure 6.3: Top view of the Living Building showing a start room, 7 rooms with different shape-changing walls types and an end room.

6.3.3 Apparatus

I implemented Living Building, a Virtual Reality mobile app that allows users to explore a wide range of shape-changing wall designs and examine their main parameters (Type of change, speed and scale).

The building consists of seven rooms each with a different shape-changing wall design. I chose seven rooms as it allows exploring seven different variations of shape-changing walls in an average of 20 minutes. Adding more rooms would result in a longer VR experience and hence, would cause participant fatigue and feelings of dizziness. Figure 6.3 shows the linear floor plan of the building. The linear floor plan offers a one-way route to explore the building, which makes the navigation in VR easier and walking distances shorter compared to other floor plans that are nonlinear. This is essential to reduce the possibility of participant fatigue. The indoor environment of the Living Building uses neutral colours for walls to eliminate any reactions that the used colours could cause. Also, the used neutral colour and lighting settings ensure the clarity in viewing the changes happening in the shape-changing walls for participants.

The user starts from the start room which shows a welcome message and a door that leads to the first room (See Figure 6.4(a)). Each room has a door that leads to the next and users follow the same sequence starting from Room 1 until reaching Room 7. The building was designed in a way so that it gradually increases the complexity of the type of change with each room. Figure 6.4 shows the different Living Building rooms. Table 6.1 describes the type of change used in rooms 1 to 7. Each room has a control panel that enables the user to manipulate speed (slow, medium, fast) and scale (single wall, two walls, all walls), as shown in Figure 6.4. Room number was added at the top of the control panel to help in identifying the location of participants during the study. Finally, the app terminates when the user reaches the end room (Figure 6.4(i)).

In addition to the Living Building rooms that allow users to explore shape-changing walls, the app also allows them to test the movement in VR before entering the Living Building. Head-tilt locomotion technique was used to enable users to move without the need for controllers by tilting

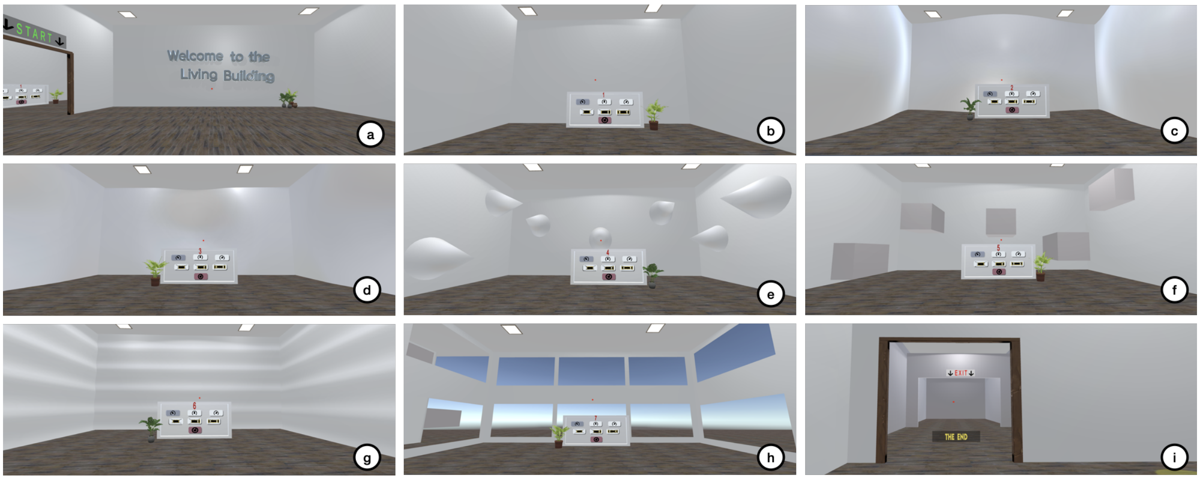

Figure 6.4: Rooms in the Living Building App: (a) Start room, (b) Room 1: Volume, (c) Room 2: Convex Curvature, (d) Room 3: Concave Curvature, (e) Room 4: Amplitude with cones, (f) Room 5: Amplitude with cubes, (g) Room 6: Zero-crossing, (h) Room 7: Porosity, (i) End room.

Table 6.1: Living Building rooms description

Room	Type	Description
Room 1		Uses the Volume type of change, where the overall volume of the wall changes while maintaining the approximate form, as shown in Figure 6.4(b).
Room 2		Uses the Curvature type of change, where the wall curves outwards creating one large convex shape, as shown in Figure 6.4(c).
Room 3		Uses the Curvature type of change, where the wall curves inwards creating one large concave shape, as shown in Figure 6.4(d).
Room 4		Uses the Amplitude type of change. Multiple control points of the wall are displaced creating a number of cone shapes on the wall, as shown in Figure 6.4(e).
Room 5		Uses the Amplitude type of change. Multiple control points of the wall are displaced creating a number of cube shapes on the wall, as shown in Figure 6.4(f).
Room 6		Uses the Zero-Crossing type of change, where the wall deforms creating a wave-like form, as shown in Figure 6.4(g).
Room 7		Uses the Porosity type of change. In this case, the wall changes creating many perforated parts in it, as shown in Figure 6.4(h).

their heads to move [301]. Users can tilt their heads 30° downwards to move and lift their heads upwards to stop.

The app was uploaded to both the Play Store (for Android users) and the App Store (for iOS users).

6.3.4 Procedure

The study procedure consists of VR experience followed by co-design activities and finally an interview. Before starting the study, a number of activities were carried out to ensure that participants are prepared for the co-design session.

Preparation: Participants who expressed an interest in participating in the study were sent an online form, containing the information sheet and the consent form before starting the study. After signing the consent form, participants were redirected to the next step of the online form and were asked to fill their delivery address details. To avoid any contact with participants during the COVID-19 pandemic, VR viewers were sent to participants directly from Amazon. Participants were asked to book a slot for the study and fill the demographics questionnaire after confirming receiving the VR viewer. Participants were asked to prepare for the study by trying the sketching tool in Google Documents, downloading the Living Building app from the appropriate app store and testing the movement in mobile VR.

Study The study was conducted online over Zoom and each lasted between 70 to 115 minutes. The study started by first giving the participant an overview explaining the purpose of the study, its main parts and the data to be collected.

VR experience Upon completing the general study overview, participants were given an overview of the VR experience and instructions on how to interact with UI elements in mobile VR and when to move to the next room. Participants were encouraged to think aloud and describe what they see, their feelings, thoughts, associations or anything that comes to their minds. They were then asked to run the app, wear the viewer and click on the Living Building button. Participants were asked to describe what they see after entering the Living Building to ensure that they clicked on the right button. The researcher then asked the participant to proceed to the first room. In the first room, the researcher explained the main panel and the different buttons that can be selected to manipulate the shape-changing walls. Participants were instructed to report the number shown at the top of the panel each time they enter a room. In the first three rooms, the researcher helped participants in selecting buttons and in encouraging them to talk (e.g. the researcher would say: select the slow speed with one wall and tell me how would you describe the change, how does it make you feel and think and whether you associate the change with anything?). In the rooms that follow, the researcher encouraged participants to think and speak aloud of which buttons they select and then describe the wall and their feelings or thoughts. After completing the exploration of each room, the researcher asked the participant to proceed to the next room. This continued until reaching the end of the seventh room and finally asking

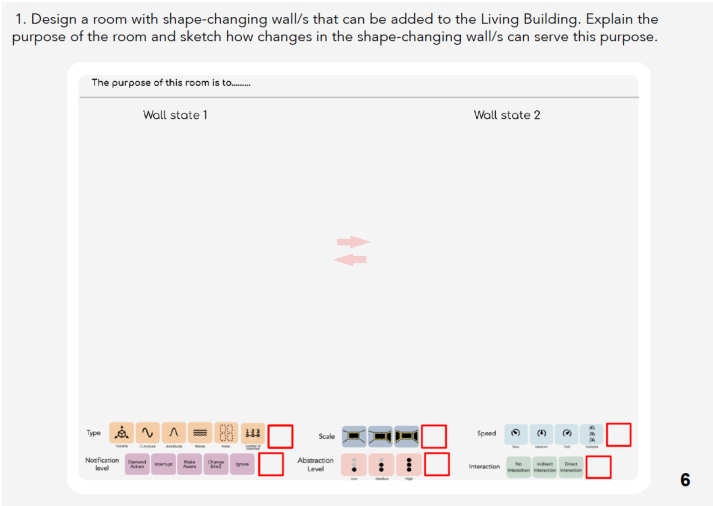

Figure 6.5: Screenshot of the first design activity.

participants to proceed to the exit door which terminates the app. After completing the VR experience, participants were asked whether they want to take a break before starting the next part.

Co-design activities: Following the VR experience, a link to the design activities sheet (Google Documents) was shared with the participant, See Appendix D. The participant was asked to open the shared activity sheet and share their screen with the researcher. To make the process more engaging, the design activities part started by asking participants to imagine wearing a designer hat and think about designing buildings with shape-changing walls. Participants were then asked to try to remember and report any shape-changing wall parameters that they have encountered during the VR experience. After that, the researcher introduced and explained the main shape-changing wall parameters that were seen during VR (i.e. type of change, scale and speed) as well as additional shape-changing wall parameters that were not encountered in VR (i.e. type of interaction, abstraction level and notification level) and their icons. As a warm-up exercise before design, participants were asked to complete a drawing activity on the shared activity sheet. Following that, the main design activities started. The first activity (See Figure 6.5) asked participants to design a room, of any purpose, with shape-changing walls that can be added to the Living Building (Design 1). Participants were asked to explain that purpose and sketch how the changes in the shape-changing walls can serve this purpose. The researcher asked questions during the design and encouraged the participant to think about each of the shape-changing wall parameters. Participants were then introduced to the term intrusiveness and were given a scenario. They were asked to assess the intrusiveness of their design (non-intrusive/moderate/intrusive) and explain the reasons behind their assessment. The researcher helped the participant to think about the different parameters that they have selected before. Based on the intrusiveness assessment, participants were asked to redesign their initial shape-changing wall design (Design 2) using the opposite intrusiveness level or to design two versions (intrusive/non-intrusive) of it if they assessed the intrusiveness of the initial design as moderate.

In the second design activity, participants were given two scenarios, each in a different setting: art gallery and hospital, and were asked to think of how might we design shape-changing walls that nudge and guide people to follow certain routes and influence their navigation decisions in both scenarios. During the design process, the researcher guided the participant into thinking about their design ideas in terms of all shape-changing wall parameters. Following that, the researcher encouraged the participant to discuss how designing shape-changing walls for these settings differs. Finally, participants were asked to think of future use cases for shape-changing walls in different settings (e.g. public space, school and work).

Interview: At the end of the study, participants were asked to reflect on the VR experience and how it helped them in visualising shape-changing walls. Participants were asked to reflect on their designs and whether and how the VR experience helped them during the design activities. Participants also reflected on the whole co-design experience.

6.3.5 Data Collection and Analysis

The entire study was audio-recorded and the participants' shared screen of the design activities was recorded. The dataset includes the audio recordings of the study and the designs that participants created in the shared design activities sheet. All audio-recordings were later transcribed using an online automated transcription tool. To clean the data, transcription files were cross-checked with the audio to detect and correct errors made by the automatic transcription such as incorrect words and speakers as well as words and sentences that were ignored by the tool.

All transcribed data were entered into Nvivo to code the qualitative data. All codes were then moved to Miro [1], which is an online collaborative whiteboard platform, to carry out the qualitative data analysis activities with the rest of the research team.

The data collected were analysed qualitatively using thematic analysis and content analysis, as described below:

Thematic analysis: An inductive thematic analysis approach was followed to analyse the initial impressions and reactions of the shape-changing walls in VR, the design activities and the interview. The initial codebook of the data was first produced. Then, team validation was conducted throughout the coding process to review and clarify codes. To collaborate with the team in constructing the affinity diagram, codes were transferred from Nvivo to Miro. Each reviewed code was represented as a sticky note in Miro. These codes were iteratively affinity diagrammed to produce categories and top level themes over the course of several team discussions.

Content analysis (intrusiveness design analysis): The parameters that participants selected for their initial designs (Design 1) along with their intrusiveness assessment were analysed. These parameters were compared with parameters selected for the opposite design (Design 2) to extract common patterns. The common patterns and categories for each parameter were first extracted. Then, two additional researchers were given these categories and asked to classify all data of each parameter independently. The average inter-rater reliability (for all parameters) using Cohen's Kappa showed an *'Excellent'* agreement between the two raters (k=0.942).

We analysed the design ideas that participants created for both the art gallery and the hospital. One researcher first extracted the common categories in these ideas. Two additional researchers were given these categories and asked to classify all design ideas independently. The inter-rater reliability using Cohen's Kappa showed an *'Excellent'* agreement between the two raters (k=0.877).

6.4 VR Experience Results

Here, I present the findings of the participants' initial reactions and impressions of the VR experience. Four main themes were identified from the analysis. These themes describe participants' reactions when encountering different types of shape-changing walls in VR. The participant number along with the type of change, speed setting (s=slow, m=medium, f=fast) and the number of walls are added to all participants quotes.

Theme 1: Provoking Positive and Negative Emotional Reactions

Participants showed a wide range of emotional reactions to the shape-changing walls. These reactions ranged from pleasant to unpleasant emotions with high and low emotional arousal. Reported emotional reactions included both induced emotions (i.e. felt emotions) and perceived emotions (i.e. expressed emotion) of the shape-changing walls [107, 279]. Different emotional reactions were found depending on the type of change, speed setting and number of activated walls. Table 6.2 shows a summary of the findings of this theme.

a) Inducing and Perceiving Pleasant Emotions

Encountering shape-changing walls in VR evoked pleasant emotions such as excitement, happiness and serenity. Participants reported induced and perceived energy, perceived sense of friendliness and trust and induced and perceived sense of calm from the shape-changing walls.

Participants reported experiencing a sense of energy and excitement while exploring the living building. In particular, P2 expressed how that the volume shape-changing wall made her feel more energetic when it was on fast speed and with one activated wall: *"It makes me feel like a bit more energetic almost"* (P2, volume, f, 1). P10, however, mentioned that while the shape-changing wall made him feel energetic, it also made him feel nervous: *"it makes me feel I guess, energetic, but also on edge"*(P10, waves, f, 1). Induced sense of energy and excitement was found in volume and waves change types, when the speed was fast and with one wall activated.

Participants also perceived feelings of energy and excitement from the shape-changing walls. For instance, P4 pointed out that she felt being inside a machine due to the perceived energy from the cubes shape-changing walls: *"It's very energetic and it's like being inside a machine"*(P4, cubes, f, 3). Further, P10 stated that the cubes that come out more than the others were more energetic compared to the other cubes and at the same time non-threatening: *"the squares seem to be coming out with different amounts from the walls, some seem to be coming further than others and I think that the ones that are coming out further are more energetic while they are moving further so that they feel more energetic but not particularly threatening"*(P10, cubes, f, 3). However, participants reported that the perceived feeling of excitement from the wall was uncomfortable: *"the whole room seems like it's excited on this speed yeah um it's like a cartoon, a cartoon expression of like excitement, um something bouncing up and down like a like a wobbly child um it it's um not very comforting i wouldn't like to spend much time in a room like this."*(P1, volume, m, 3). Perceived sense of energy and excitement was noticed in the volume and cubes types of change with medium and fast speed settings and when one and three walls were activated.

Participants stated perceiving a sense of friendliness from the shape-changing walls. For instance, P10 describes the cones type of wall change when it is on slow speed as *"separate entities that are moving in unison, rather than one thing and that seemed more friendly, I guess."* (P10, cones,s,3). Perceived friendliness was found in cones and concave curvature types of change with slow and fast speed settings and when three walls were activated.

In addition, participants reported experiencing a sense of trust from the pleasant shape-changing walls. P7 explains how she felt safe when she tried the slow speed in the volume type of change as the wall did not look dangerous: *"The slow movement, it's more soft I feel safe, I feel it's okay because it's moving, but it's not like it's not scary or it does not seem like something that is not safe or is dangerous"*(P7, volume, s, 1). Induced sense of trust was noticed in the change types: volume, concave curvature, cones, when the speed is slow and with one wall.

Participants expressed that the shape-changing walls made them feel calm and relaxed: *"the slow speed is quite relaxing"*(P4, convex curvature, s, 3), *"it feels very calming"* (P20, waves, s, 1), *"It's oddly relaxing"* (P18, volume, s, 1). P3 stated that she would look at the waves wall change to make her relax: *"This is quite pleasant, this is I think I probably like to look at this If I wanted to relax"*(P3, waves, s, 1). In addition, participants reported that it felt more relaxing with three walls activated in the waves type of change: *"Actually having the three walls of immersion on this one actually felt more relaxing"*(P18, waves,s, 3). Induced sense of serenity was found in all types of change and in all speed and wall settings.

Participants also reported perceiving calmness and relaxation from the the shape-changing walls: *"it feels quite serene"*(P20, volume,s,1). P19 described that the wall is relaxed and calm after she realised that it was moving backwards: *"P19: In the beginning, I didn't notice that it's moving backwards, right now, when I analysed the light and the shadow then I realised that actually it is moving backwards, so basically, I know it's moving but at the beginning I didn't realise, I didn't know whether it's moving forward or backward, so I can feel the movement, it is relaxed, it is calm"*(P19, concave curvature, s, 1). Perceived sense of serenity was noticed in all types of change except holes, with all speed settings and with one and three activated walls. P10 described how the perceived sense of serenity from the wall induced calmness in him: *"Oh, this* *one is very slow. Yeah, it kind of, it's kind of serene it's kind of calm. It yeah, it makes me think of being.. It makes me relaxed"* (P10, concave curvature, s, 3).

b) Inducing and Perceiving Unpleasant Emotions

Experiencing shape-changing walls in VR has resulted in a number of unpleasant emotions. Participants described the perceived sense of anger and aggression from the shape-changing walls and the induced and perceived sense of fear.

Participants reported perceiving anger from the shape-changing walls. P20 described that the cube that is *" on the right is coming out quite, It feels quite close to me, so it feels like when there's three of them, It feels even more kind of angry"*(P20, cubes, m, 3), while P19 expressed that she felt that *" the whole room has gone mad"*(P19, volume, f, 3). Perceived anger was noticed in the volume, cones and cubes change types, with medium and fast speeds and on one and three activated walls.

In addition, participants expressed perceiving feelings of aggression from the wall. P20 mentioned that she perceived the wall as aggressive even when it was on a slow speed but not as much as threatening as the fast one: *"It still feels aggressive but not quite as not quite as menacing as when it's fast."*(P20, cones, s, 1). Perceived sense of aggression was found in the cones and cubes types with all speed settings and with only one wall activated.

Participants indicated that certain shape-changing walls induced annoyance. For example, P11 mentioned that the waves type of change with the fast speed and with three activated walls is: *"A bit too much going on visually."*(P11, waves,f, 3), while P13 found the cubes type of change with these speed and wall setting as:*" Irritating visually and I can imagine that it would be pretty anxiety inducing to be in a real room where that was happening."*(P13, cubes, f, 3). Participants stated being annoyed in the volume, cones, cubes and waves types of change, with slow (one only when the shape was bothering the participant) and fast (mostly with fast) speeds and when one and three walls were activated.

Fear was described in many ways, including reporting the felt emotions and the perceived emotions of the wall, describing scary actions and remembering scary memories. For example, P18 mentioned that the cubes type of change *"Makes me feel a little uneasy like it's coming quite a lot closer than the other ones, well, by going above me almost, it feels a bit uneasy"* (P18, cubes, s, 3) while P6 expressed surprise and fear upon entering this room: *"Whoa, this one is actually a bit anxious, It's like big file cabinets coming towards me."*(P6, cubes, m, 1).

Participants felt overwhelmed and anxious by the threatening and scary wall: *"That's definitely feeling threatening, a bit overwhelmed, I guess. Yeah, and potentially a little bit confused as well."* (P10, volume, f, 1), *"Fast with coming out each of the walls is is a bit kind of chaotic and scary. The one on the right hand side in particular is coming quite close to me quite sharp corners and that's yes that provokes a slight feeling of anxiety"* (P11, cubes, f, 3). P1 mentioned that activating three walls on fast speed in the cones type of change is: *"More threatening. Again, I feel like I'm being trapped in some sort of obscure torture chamber"* (P1, cones, f, 3). Participants also expressed fear from the wall that was looking like a monster threatening them: *"Slow speed on full room is a bit threatening um it's a bit like a big breeding thing is waiting to eat me or something like, yeah just sitting there really anticipating swallowing me."*(P1, volume, s, 3), *"It is menacing I think because you can only because of the way the panel is placed you can only really see the flex happen at the top of the ceiling quite gradual. So it feels like something some large monstrous change gradually happening."*(P10, convex curvature, s, 1). Fear was found in all types of change, in all speed settings, and when one and three walls were activated.

In addition, participants reported a number of actions that the shape-changing walls were doing which provoked fear in them. For instance, participants mentioned actions that the wall is trying to do such as hitting, crushing and pushing: *"I feel like, yeah, they're just crushing on to me and a bit pushing me to the corner, even though I know I'm standing probably in the middle of the room"* (P6, volume, m, 2), *"It's quite it's a bit fast. I felt a bit like everything's like trying to hit me."*(P2, cubes, f, 3), *"...especially because some of these are down at floor level, these could probably hurt you like if you were over there and one of them ran into you, it would knock you over."*(P4, cubes, f, 3). P16 describes his experience with the cubes type of change when it is on fast speed with three activated walls as being inside a machine: *"So it's just look like a some squeezing or stamping machine here and I'm here inside of it. So it's quite unpleasant and feels I'm being squeezed"*(P16, cube, f, 3). Such scary actions were reported in all types of change except concave curvature and in all speed and wall settings.

Some participants described scary analogies such as prison, trap room, scary movies, video games: *"With the three walls and with fast, it's just feels even more like a like a trap room."*(P20, cones, f, 3), *"Reminds me of like the video games where you have to like get out of a room before it crushes you."*(P13, volume, s, 1), while others remembered scary memories such as childhood nightmares: *"I used to have a nightmare when I was a child that used to do this."*(P9, volume, f, 3).

Theme 2: Uncovering Affordances of Shape-changing Walls

This theme describes the affordances of shape-changing walls reported by participants, which include clear affordances that call for particular actions, inviting affordances that invite people to do actions (but not particular actions) or repel them from doing things and unclear affordances in which participants tried to understand the affordances that the shape-changing wall was trying to convey. Table 6.3 summarises the findings of this theme.

a) Concrete perceived affordances of action possibilities

Participants stated that the cubes type of change affords certain actions such as sitting, creating stairs and even to be used for games:*"I feel if they stop moving, if they come forward and stop moving its kind of providing affordance for people to sit on it."*(P19, cubes, s, 1), *"All right, now we have blocks moving square blocks. Oh, that's nice. It seems like they are forming a kind of stairs or helpful features at least."*(P12, cubes, m, 1).

Table 6.2: Summary of Theme 1 (Provoking Positive and Negative Emotional Reactions) findings

		Emotion	**Change Type**	**Speed**	**Scale**
Theme 1	Inducing and Perceiving Pleasant Emotions	Induced Energy	Volume Waves	Fast	One wall
		Perceived energy	Volume Cubes	Moderate Fast	One wall Three walls
		Perceived friendliness	Cones concave curvature	Slow Fast	Three walls
		Induced trust	Volume Concave Curvature Cones	Slow	One wall
		Induced sense of serenity	All types	All speed settings	All wall settings
		Perceived sense of serenity	Volume Concave Curvature Convex Curvature Cones Cubes Waves	All speed settings	One wall Three walls
	Inducing and Perceiving Unpleasant Emotions	Perceived anger	Volume Cones Cubes	Moderate Fast	One wall Three walls
		Perceived aggression	Cones Cubes	All speed settings	One wall
		Induced annoyance	Volume Cones Cubes Waves	Slow Fast	One wall Three walls
		Induced fear	All types	All speed settings	All wall settings

Participants also expressed that they perceive directional information from the cones type of change. For instance, P2 mentioned the fast speed: *"Kind of looks like they're pointing me in the direction behind me and I want to turn around and see what they're pointing at"*(P2, cones, f, 1) whereas the slow does not point at a particular direction: *"I don't find it pointing me in any direction now because it's not like a really quick, like a point movement, it's like very slow."*(P2, cones, slow, 3). Participants also stated that the fast speed points at them: *"It is like it's kind of pointing at you."*(P18, cones, f, 1).

Participants reported that the cubes type of change carries a hidden message in its changes: *"So, when I look at it is, I think, the room is trying to show some kind of pattern and this pattern carries..maybe carries a meaning or messages of people whoever stepped in this room."*(P19, cubes, f, 3)

Participants also indicated a range of actions that the shape-changing walls triggered in them such as jumping, climbing and dancing: *"This just kind of feels like I'm in a fun house. Looks like the spongy walls that I could like jump against and bounce off."*(P2, concave curvature,f, 3), *"So it reminds me of climbing walls, something that makes me like want to go up to them and like try to climb up on them or something."*(P3, cubes, s, 3).

Participants expressed that they perceived that wall was asking them to do something instantly: *"It was like kind of giving some rush feeling to do something immediately."*(P15, volume, m, 1)

b) Inviting and repelling Affordances
Rather than stating affordances of action possibilities, participants reported that the shape-changing walls were providing an inviting affordance and that they invite interactions: *"This one is like could be inviting depending on like what it..if it just suggests anything then I would go approach it."*(P6, cubes, s, 1), *"I don't feel pressured by it. I don't feel it's aggressive. So, um, so I think it's kind of inviting me to to enjoy something or to do something here."*(P19, concave curvature, f, 1). P19 explained that reducing the speed made the room inviting: *"I think this is much better because um when the speed is reduced, so the whole purpose of the building, for me at least, is changed to it's changing and the purpose changed from refusing people to step in to something that invite people to come in and do something with a building."*(P19, volume, s, 3). In addition, P3 expressed that the cubes type of change invites playful interactions: *"Kind of like seems to kind of like invite a bit more playing with them or something...."*(P3, cubes, s, 3). He continued, saying that one wall does not invite playful interactions whereas activating three walls does: *"I guess if it's just one wall, it kind of makes you focus your attention and I think if it is a single wall, It makes you think of it more as something to be looked at, rather than kind of played with, whereas if it's like all the walls, it seems more like is there for you to kind of interact with more I guess."* (P3, cubes, s, 1 and 3).

In addition, participants mentioned that they were intrigued and curious to approach: *"The ones on the lower... I might be curious to go and touch it it looks, it looks not that scary. I mean, the colour and the shape doesn't look scary. So if it's there. I probably would go touch it"*(P6, cones, f, 3). While other participants were curious to touch and feel the wall: *"It's quite interesting, I wanna go and like feel it what does it feel like."*(P2, convex curvature, f, 3).

On the other hand, participants also mentioned that certain shape-changing types with certain speed and wall settings were uninviting and repelling: *"It feels unwelcomed like go away"* (P6, cones, f, 3). In other cases, participants reported that the wall was trying to convey messages that give a sense of threat and danger: *"it almost gives you like kind of this alarm feeling like Whee, Whee, Whee [participant makes sounds] like there's a fire. Get out."*(P17, concave curvature, f, 3), *"And it looks like some on some something some alert about danger or about something misfunction."*(P19, cubes, f, 1).

c) Trying to Understand Affordances of the Shape-changing Walls
Participants mentioned that they were trying to understand what the shape-changing wall was trying to convey through the physical changes: *"It's not clear what it's trying to say, or what it's for or why you would want it"*(P4, holes,f, 3). P1 expressed that he felt the wall change looks like it has a purpose but it was not clear what the purpose is: *"I feel they feel purposive but i don't know what that purpose is."*(P1, cones, f, 1). P3 stated that he is curious to understand why the

Table 6.3: Summary of Theme 2 (Uncovering Affordances of Shape-changing Walls) findings

		Affordance	Change Type	Speed	Scale
Theme 2	Concrete perceived affordances of action possibilities	Specific actions	Cubes	Slow Moderate	One wall Three walls
		Information	Cones	Slow Fast	One wall Three walls
		Hidden message	Cubes	Slow Fast	One wall Three walls
		Trigger actions in people	Volume Cubes Concave Curvature	All speed settings	One wall Three walls
	Inviting and repelling affordances	Inviting	Volume Concave Curvature Cubes	Slow Fast	One wall Three walls
		Evoking curiosity	Volume Cones Cubes Convex Curvature	Slow Fast	Three walls
		Uninviting	Volume Cones Cubes Concave Curvature Waves	Fast	One wall Three walls
	Trying to understand affordances of Shape-changing Walls	Unclear affordances	Volume Holes Cubes Cones	Slow Fast	One wall Three walls

wall was changing in that way: *"I guess it makes a bit more curious about it as to why it's moving the way it is."*(P3, volume, s, 1).

Theme 3: Experiencing Sensory Illusions

This theme describes the sensory illusions that participants experienced in VR. These include pleasant illusions such as changes in body temperature and hearing sounds as well as unpleasant illusions such as lack of balance and sickness. Table 6.4 summarises the findings of this theme.

a) Pleasant Illusions

Exploring shape-changing walls in VR have resulted in a number of pleasant sensory illusions, including cross-modal illusions that relate directly to the body and illusions that relate the body's relation with the surrounding space. Participants reported a number of cross-modal illusions that relate to the body such as hearing sounds, changes in body temperature and changes in body weight. For instance, participants mentioned that they started to hear sounds and noises as they were looking at the shape-changing walls: *"I'm getting a bit of the what's it called when you have one sense, feeding into another one like I feel like I'm hearing it as it's moving quickly. like I always feel like I can hear it......I noticed it a bit on the three walls and fast, but much more with the single wall."*(P18, cubes, f, 1 and 3), *"I Almost hear noises because you know that these types of movement couldn't be without noise."* (P5, waves, f, 3). While others stated that they started to think about sound during this visual experience: *"it makes me think now, it's funny,* *but I'm thinking about sound, because it's moving like in a rhythm. Yeah, as if it was like, I don't know, like with music or something like that."*(P7, volume, f, 3). Cross-modal illusion of sound was noticed in the volume, cones, cubes, waves and holes type of change with all speed settings and with one and three activated walls.

Participants expressed that they felt cold in the holes room/type of change: *"I selected single wall and slow, it feels very cold, I guess chilled."*(P10, holes, s, 1). P6 started to wonder about the room temperature and continued saying that it feels cold: *"Weirdly It really makes me wonder, What's the temperature, like in the room for this one......but for now, the default speed is ok for me like calming. It makes me feel cool like like if it's summer I feel like the room will be cooler."* (P6, convex curvature, m, 1). Changes in body temperature illusion occurred in holes and convex curvature change types and with slow and medium speeds and on one wall.

In addition, participants expressed experiencing changes in body weight: *"with three walls and high speed. Yeah, totally flying up. Yeah, it seems like I'm in an elevator a lift going up....makes me feel with no with weight, no sense of weight."*(P12, waves, f, 3). P6, on the other hand had an illusion about the weight of one of the cubes and described as heavy: *"Whoa, this one is actually a bit anxious. It's like a big file cabinets coming towards me especially the front one and the one on the bottom seems very heavy"*(P6,cubes, m, 1). Weight illusions occurred in cubes and waves types of change with medium and fast speeds and with one and three activated walls.

Participants reported illusions that relate to the body's relation with the surrounding space such as space vastness, room ventilation and motion illusions. For instance, P6 explained that the medium speed in the holes type of change makes the room larger: *"Yeah, where the default one is nicer it is like as It makes me feel like the room is larger like because I'm extending out towards the window or outwards."*(P6, holes, m, 3). Sense of vastness illusion occurred in the holes and volume types of change and with medium and fast speeds and with three walls activated.

Also, participants expressed illusions of space ventilation: *"I think is the opposite of the first one, instead of being like missing air, It's like, it seems to be very well ventilated here."*(P12, concave curvature, m, 3). P16 mentioned that the room is filled with air that is stretched: *"Feel like like I'm in some air, air filled room and,but it's not as it's not like I'm stretched and squeezed. So I don't feel as stretched and squeezed as before, maybe just yeah..I feel more like the room is, so there are some air in the room that is stretched and squeezed but not me."* (P16, convex curvature, f, 3). Illusions about room ventilation occurred in volume, convex curvature and concave curvature change types with all speed settings and with three activated walls.

Participants reported motion illusions such as walking and falling. For example, P5 described illusion of walking while standing still in front of the volume type of change: *"It feels like I'm just walking, something like that. It's just, I'm not standing. But it is.... I'm moving towards the wall and just going back from the wall, this type of thing , I guess....yeah I don't move right now, but while standing in front of that it feels it is moving I think I'm just going towards the wall and going away from the wall."*(P5, volume, s, 1). P2 mentioned that the holes type of change made her feel like falling from the sky: *"I've just changed it to slow, kind of feels like I'm falling. well, it's like moving away from me, It's like I'm falling down from the sky, but when it's moving towards me, It feels like I'm falling onto it, a bit strange."*(P2, holes, s, 1). Motion illusions occurred in volume and holes types of change with slow speed and one wall activated.

b) Unpleasant Illusions

In addition to the pleasant sensory illusions that affected the participants' bodies directly and their surrounding space, participants also experienced unpleasant illusions which occurred either from the shape-changing walls, using VR or both. Participants reported feeling sick and nauseous: *"so it makes me feel a bit queasy."*(P1, volume, s, 1), *"Can't even look at it makes me feel really sick."*(P9, cubes, m, 3). P6 mentioned that she felt unsettled because the wall seemed ill and was experiencing a stomach cramp: *"It's it's unsettling, it feels like feel like it is ill, It's like a stomach cramp"*(P6, convex curvature, f, 3). Sickness feelings were reported in volume, convex curvature, concave curvature, cubes and waves change types and with all speed and wall settings.

Participants also reported experiencing lack of balance with the shape-changing walls: *"It feels a little disorientating."*(P18, convex curvature, s, 3), *"Oh, this one makes me feel dizzy."*(P15, volume, f, 3). P18 mentioned that the room felt like it is squiffy in the convex curvature change type: *"It might just be the VR but it kind of makes the whole room look like it's going squiffy, which is a bit psychedelic"*(P18, convex curvature, s, 3). Lack of balance was noticed in volume, convex curvature, cones and waves and with slow and fast speeds and with one and three walls activated.

Theme 4: Describing metaphors and making associations with real-world objects and experiences

This theme describes the different metaphors and associations that the participants used to describe the shape-changing walls. These metaphors and associations were classified into moving and non-moving things. Moving things include all descriptions of shape-changing walls that use anthropomorphic metaphors as well as descriptions that relate to moving mechanical objects. Non-moving things include using metaphors of real-world objects or experiences to describe shape-changing walls. Table 6.5 summarises the findings of this theme.

a) Moving things

Many participants used anthropomorphic metaphors to describe the different shape-changing wall types. For instance, participants referred to certain shape-changing wall types as humans, creatures and living things: *"I think the single wall is quite biological it feels quite like so of human"*(P10,volume, f,1), *"I feel the whole room is some kind of a creature"* (P19, cones, f, 3). In addition, P11 and P1 described their feelings of being inside a living thing that is performing some kind of a process such as breathing and digestion: *"I guess it's like being inside someone's rib cage as they are breathing or something."* (P11, volume, s, 3), *"It feels like I'm stuck inside one organism which is maybe trying to digest me or something."* (P1, cones,f,3). Also, some participants reported that the shape-changing walls had certain human qualities such as intelligence: *"It*

Table 6.4: Summary of Theme 3 (Experiencing Sensory Illusions) findings

		Illusion	**Change Type**	**Speed**	**Scale**
Theme 3	Pleasant illusions	Sound illusions	Volume Cubes Cones Waves Holes	All speed settings	One wall Three walls
		Change in body temperature illusion	Convex Curvature Holes	Slow Moderate	One wall
		Weight illusion	Cubes Waves	Moderate Fast	One wall Three walls
		Sense of vastness illusion	Volume Holes	Moderate Fast	Three walls
		Ventilation illusion	Volume Convex Curvature Concave Curvature	All speed settings	Three walls
		Motion illusion	Volume Holes	Slow	One wall
	Unpleasant illusions	Sickness	Volume Convex Curvature Concave Curvature Cubes Waves	All speed settings	All scale settings
		Lack of balance	Volume Convex Curvature Cones Waves	Slow Fast	One wall Three walls

feels like individual things which are moving in concert and it feels like they are intelligent and have some sort of slightly benign calm but slightly uncanny group intelligence." (P1,cones,s,1). anthropomorphic metaphors were noticed in all types of change except Waves, all speed settings and in one and three walls.

Participants made associations with moving mechanical objects while describing shape-changing walls. For example, P17 described shape-changing walls as passing cars because of the square shape of the Amplitude(cube) wall: *"I think because of the square shape, it does give me sort of this feeling of like vehicles coming at me or like driving past me."*(P17, cubes,s, 1). Other participants described shape-changing walls as a conveyor belt, squeezing machine and factory: *"It feels like a conveyor belt or like something like that like a machinery processing, but it still feels quite nice. It feels like it invokes a sense of efficiency."*(P20, waves,f, 1), *"It feels like some sort of factory thing, some sort of abstract factory"* (P1,cubes,f,3). Metaphors that relate to machinery were found with Volume, Waves, Cubes, Convex Curvature and Cones types of change, with slow and fast speeds and in one and three walls.

b) Non-moving things

Many participants made associations of shape-changing walls with real-life objects. For instance, participants described the cubes change type as *"drawers in a filing cabinet."*(P20, cubes,f, 1),

Table 6.5: Summary of Theme 4 (Describing metaphors and making associations with real-world objects and experiences) findings

		Metaphor	Change Type	Speed	Scale
Theme 4	Moving things	Anthropomorphic metaphors	Volume Convex Curvature Concave Curvature Cubes Cones Holes	All speed settings	One wall Three walls
		Mechanical objects	Volume Convex Curvature Waves Cubes Cones	Slow Fast	One wall Three walls
	Non-moving things	Real-life objects	All types of change	All speed settings	All scale settings
		Real-life experiences and events	Volume Convex Curvature Cones Cubes Holes	All speed settings	One wall Three walls

waves change type as *"curtains"*(P15,waves, s, 3) and as a *"TV without signal"*(P16,waves,f,1), convex curvature change type as *"trampoline"*(P2, convex curvature, f, 1), holes type of change as *"windows"*(P7,holes,m,1) and concave curvature as *"paper"*(P7,concave curvature,f,3). Participants also described viewing the shape-changing walls as *"weird art installation"*(P9,cones,s,3). Making associations with real-life objects was noticed in all types of change and all speed and scale settings.

In addition, several participants reported associating shape-changing walls with real-life experiences and events. For example, participants described fun and playful experiences such as party, music and gaming while encountering the shape-changing walls: *"When I set the fast speed, it feels like it's a party."*(P17, cones,f,3), *"It just keeps going back to the video game thing and these are all the different obstacles that you have to try to jump on to get across a lava pit."*(P13,cubes,m,1). Also, participants reported remembering past events when experiencing the shape-changing walls. For example, P17 mentioned remembering childhood memories:*"Actually, it's kind of fun..it is kind of like childhood, like I'm jumping up and down like I'm in a bouncy house."* (P17,volume,f,3). P18 also reported remembering an old video game: *"Weirdly it reminds me of a really old video game...It is quite positive and I feel there's a lot of nostalgia from that video game playing into that."*(P18, cubes, s,1). Making associations with real-life experiences and events was noticed in Volume, Convex Curvature, Cones, Cubes, Holes types of change, with all speed settings and in one and three walls.

6.5 Co-Design Activities Results

In the first design activity, participants were asked to design a room with shape-changing walls for any purpose they choose. This has resulted in 18 different design ideas. Figure 6.6 shows examples of the designs created by participants in the first design activity. The purpose of these ideas were grouped into two categories: functional purposes and hedonic purposes, with 9 ideas in each group. Ideas in the functional purposes group include designing for communication (e.g. designing a room that communicates weather information), adaptive affordances (e.g. designing a room that changes its size when needed), behaviour change, exercise and security. Hedonic purposes group involves designing for emotion regulation (e.g. designing a room to calm people down), purely aesthetical aim (e.g. designing a room with a shape-changing art piece) and entertainment such as games. A summary of the different shape-changing walls parameters participants used in their designs is presented below.

Change Type: Among these design ideas, seven participants chose to design with the amplitude type of change (using various shapes such as cubes or cones), four participants chose the volume type, four participants selected the waves type, three participants selected the holes type and two participants chose to design with concave curvature change type. All participants used one type of change in their designs except two participants who used two types (waves with holes and amplitude with holes).

Speed: Ten participants chose a variable speed for their designs (i.e. the speed of the shape-changing wall can be slow, medium or fast depending on how the participant chose to vary the speed). Three participants chose slow speed and medium speed and two participants used a fast speed for their designs.

Scale: Twelve participants selected to apply the shape-change on all room walls, four participants selected one wall and two participants chose to apply it on two to three walls.

Interaction: Nine participants selected indirect interaction, eight participants chose direct interaction and three participants chose no interaction for their shape-changing wall design. All participants used one interaction type in their designs except two participants who chose to use two interaction types in their designs (direct interaction with no interaction and direct interaction with no interaction).

Notification level: Twelve participants chose a notification level of make aware for their designs. Three and two participants selected change blind and interrupt levels respectively and one participant chose demand action notification level.

Abstraction level: was applicable only on design ideas of three participants since their designs involved information communication. Two participants selected a low abstraction level and one participant selected a medium level.

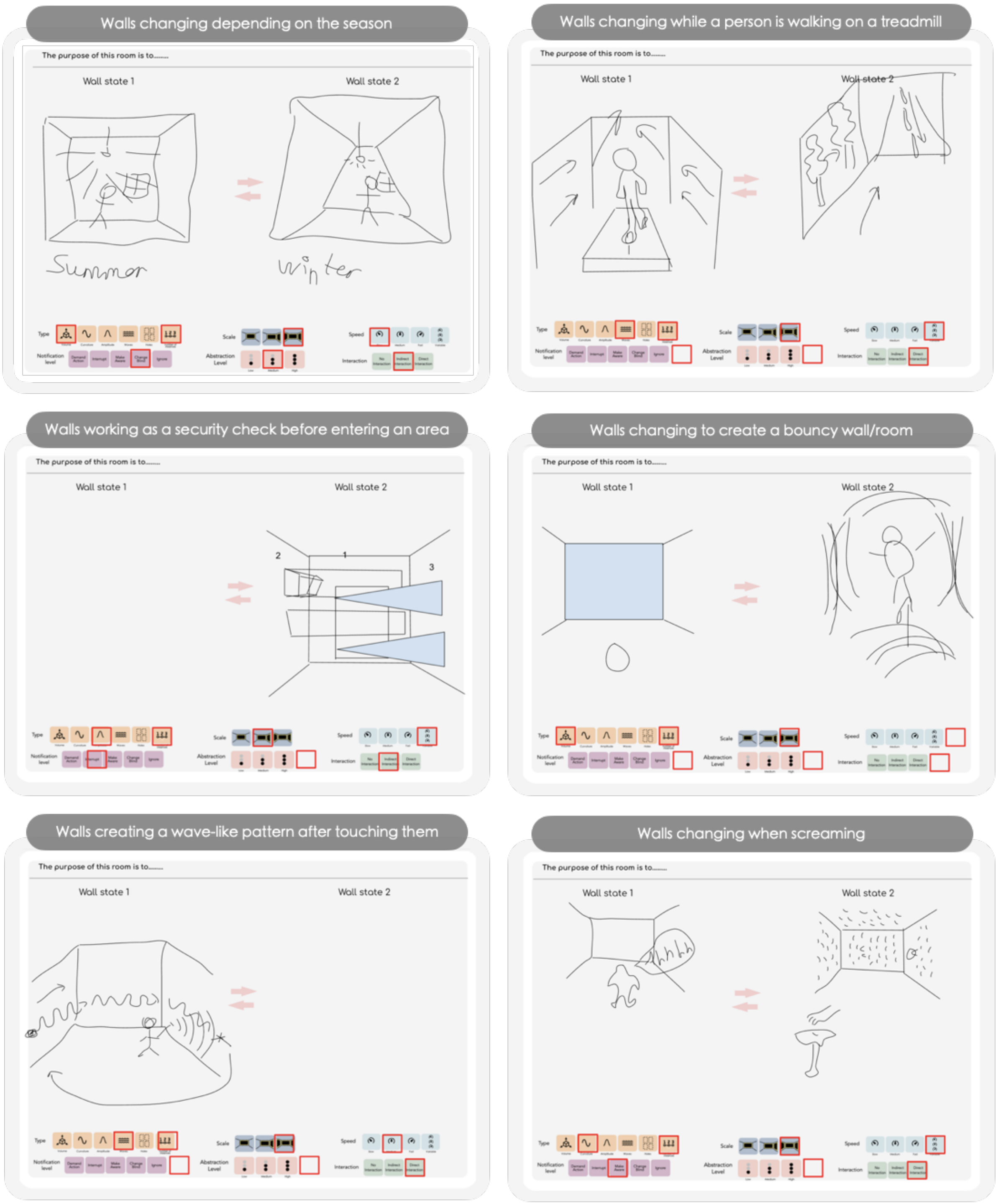

Figure 6.6: Examples of designs created by participants in the first design activity showing functional and hedonic purposes including, adaptive affordances, exercise, security, entertainment and stress relief.

6.5.1 Designing for Intrusiveness of Shape-Changing Walls

Fourteen participants rated their designs (Design 1) as intrusive and only four participants rated them as non-intrusive.

Following the rating of the level of intrusion of the shape-changing wall designs, each participant altered their initial design and designed a shape-changing wall with an opposite intrusion level (Design 2). Participants changed various parameters to either make a design intrusive or non-intrusive. The differences between the Design 1 and Design 2 were examined and analysed. Based on this analysis, the following categories, which explain how each parameter relates to intrusion, were produced:

Type of change (n=9): Three categories were identified:

1. Change type (n=5): Both groups of participants who rated their initial designs as intrusive and non-intrusive chose to alter their opposite design by changing the type. To make the design less intrusive or non-intrusive, participants (n=3) changed the type of their initial design and used Curvature and Holes types. However, participants (n=2) changed the type of change in their initial design to Amplitude to make it intrusive.

2. Add another type (n=2): Both groups of participants who rated their initial designs as intrusive and non-intrusive updated their opposite design by adding another type. Participants (n=1) who rated their initial design as non-intrusive added another change type (e.g. amplitude) to make it intrusive. In addition, participants (n=1) who rated their initial design as intrusive chose to add another change type (e.g. Holes) to make it non-intrusive.

3. Remove a type and use one type only (n=2): Participants who used two types of change in their initial design and rated it as intrusive chose to remove one of these types of change and use only one type to make the altered design less or non-intrusive.

Speed(n=14): Two categories were identified:

1. Reduce speed: participants (n=11) who rated their initial design as intrusive reduced the speed of the shape-changing wall design to make it less or non-intrusive.

2. Increase speed: participants (n=3) who rated their initial design as non-intrusive increased the speed of the shape-changing wall design to make it intrusive.

Scale (n=9): Two categories were identified:

1. Reduce scale: participants (n=7) who rated their initial design as intrusive reduced the number of walls to make the shape-changing wall design less or non-intrusive. For example, participants who first chose to apply the shape change on all walls, reduced the number of walls to one shape-changing wall to make the design less or non-intrusive.

2. Increase scale: participants (n=2) who rated their initial design as non-intrusive increased the number of walls to make the shape-changing wall design intrusive. For instance, participants chose to apply the shape-change on all walls to make the design intrusive.

Interaction (n=4): Three categories were identified:

1. Change to direct interaction: participants (n=2) who rated their initial design as intrusive changed the type of interaction from indirect or no interaction to direct interaction to make the shape-changing wall design less or non-intrusive. Participants explained that the shape-changing wall can be less intrusive by giving the user more control over the wall (e.g. to control speed).

2. Change to indirect interaction: participants (n=1) who rated their initial design as intrusive changed the type of interaction from direct interaction to indirect interaction.

3. Change to no interaction: participants (n=1) who rated their initial design as non-intrusive changed the type of interaction from direct interaction to no interaction to make the shape-changing wall design intrusive. Participants explained that by not offering any control over the shape-changing wall and by making it always on, the wall design can be intrusive.

Notification Level(n=3): Two categories were identified:

1. Reduce notification level: participants (n=2) who rated their initial design as intrusive reduced the notification level to make the shape-changing wall design less or non-intrusive. For example, one participant changed the notification level from Interrupt level to Make Aware, while another participant changed it from Make Aware level to Change Blind.

Abstraction level(n=2): Two categories were identified:

1. Decrease abstraction level: participants (n=1) who rated their initial design as non-intrusive decreased the abstraction level of the shape-changing wall design to make it intrusive. For instance, P10 explained that the design can be intrusive by making it less abstract and more direct in terms of the information presented.

2. Increase Abstraction level: participants (n=1) who rated their initial design as intrusive increased the abstraction level of their shape-changing wall design to make it less or non-intrusive. For example, P1 mentioned that rather than presenting individual information about breathing, averaged data (higher abstraction) would make the design less or non-intrusive.

In addition to the categories extracted from the changes in the given shape-changing wall parameters, participants reported other aspects that they thought are related to the intrusiveness of shape-changing walls and were not covered in the studied parameters. These include shape size (e.g. in case of using Amplitude type), shape smoothness, movement type, modality and colour.

Shape size: participants mentioned that using smaller shapes of cubes or cones in the Amplitude change type would make it less or non-intrusive, whereas others mentioned that designs can be made intrusive by increasing the size of such shapes.

Shape smoothness: participants reported that using smooth and rounded edges of shapes (e.g. cubes or cones in Amplitude type) rather than sharp edge would make the design non-intrusive.

Movement type: participants explained that cyclical movement of the shape-changing walls can make it intrusive and that on demand shape-change would make designs less or non-intrusive. One participant also mentioned that the synchronous movement of shapes (in case of the amplitude type) would make it less intrusive compared to asynchronous movement.

Modality: participants mentioned that the shape-change modality is considered in itself intrusive and using another modality would make wall designs less or non-intrusive.

Colours: participants reported that the use of calm colours for the shape-changing walls would result in a less intrusive wall design.

6.5.2 Designing to nudge and influence navigation decisions

Participants described wide range of ideas for designing shape-changing walls to nudge people to follow certain routes and influence their navigation decisions within an art gallery and hospital settings. Participants were asked to think of and design one idea for each setting, however, in around 11 cases in both the art gallery and hospital activities, participants produced two ideas. Below is a summary of the used parameters.

Change Type: Participants used all types of change in both settings, with the waves type (n=13) being used the most followed by amplitude (n=10) then volume(n=9), curvature(n=8) and finally the holes type (n=7). In the art gallery activity, waves type (n=8) was most frequently used followed by curvature (n=6) then volume (n=5), amplitude (n=4) and finally holes (n=1), whereas in the hospital activity, amplitude (n=6) and holes (n=6) types were used the most followed by waves (n=5) then volume (n=4) and finally the curvature type (n=2).

Speed: Participants also used all possible speed settings in the art gallery and hospital activities. In both activities, slow speed (n=17) was used the most followed by medium speed (n=13.5) and then fast (n=7.5) and variable (n=4) speeds. Adding 0.5 to the previous counts occurs when participants mention two speeds in their design (e.g. slow to medium). In this case, 0.5 goes to slow and the other 0.5 goes to medium.

Scale: Participants applied their shape-changing wall designs on various wall settings. In both of the art gallery and hospital activities, participants chose to apply the shape-changing walls most of the time on two to three walls of a corridor or room (n=26), followed by one wall (n=15) of a corridor or a room and then finally all walls (n=1) of a corridor or room.

Interaction: Participants used two types of interaction in the art gallery activity: direct interaction and indirect interaction, with indirect interaction (n=17) being the most frequently used type of interaction followed by direct interaction (n=5). In the hospital activity, all types of interaction were used; direct, indirect and no interaction, where direct interaction (n=9) was used more often, followed by indirect interaction (n=8) and then no interaction (n=5).

Notification Level: Participants employed different notification levels for their shape-changing wall designs in both activities. Ideas in both of the art gallery and hospital activities used Make Aware level (n=28) most of the time, followed by Interrupt level (n=12) and finally Change Blind level (n=4). Demand Action level was only used once in the hospital activity.

Abstraction Level: Abstraction level was only applicable to two design ideas; one idea in each of the art gallery and hospital activity where participants designed shape-changing walls to communicate information. In both cases, the used abstraction level was low.

A total of 47 ideas were produced in both of the art gallery and hospital activities. Two themes were generated to answer the question of *how shape-changing walls can be designed to nudge people to follow certain routes and influence their navigation decisions*; "Encouraging Nudges" and "Discouraging Nudges". Overall, 74.5% of the design ideas fell into the encouraging nudges theme, while the remaining 25.5% of the ideas belonged to the discouraging nudges theme.

Theme 1: Encouraging nudges

This theme describes design ideas of shape-changing walls that attract and encourage people to follow certain routes. Some design ideas occurred more frequently than others in both the art gallery and hospital activities. For example, the most popular design idea was to use shape-changing walls of the waves type which show vertical waves that lead towards a direction (See Figure 6.7 (a)). Another idea that occurred in both the art gallery and hospital activities is to use shape-changing walls with the curvature type to attract attention and invite people in. Participants also mentioned the use of shape-changing walls of the holes type that open to let people in and allow entering.Another idea in the encouraging nudges theme that occurred repeatedly (but only in the art gallery activity) involves using shape-changing walls of the curvature type which curves to make corridors wider, as shown in Figure 6.7 (a).

Other design ideas that occurred less in this theme include shape-changing walls of the amplitude type that show arrows or words to show direction, shape-changing walls of the volume type that are used to attract attention (since they show a breathing-like effect) and using shape-changing walls of the waves type to draw the attention of the passer-by.

Theme 1: Discouraging Nudges

This theme describes design ideas of shape-changing walls that discourage and deter people from following certain routes. One idea that occurred repeatedly is to use shape-changing walls of the amplitude type which show cubes or spikes that block movement towards certain directions, as shown in Figure 6.7 (b). Another idea that occurred only in the art galley is to use shape-changing

Figure 6.7: Examples of designs created by participants in the two identified themes: (a) Encouraging nudges (b) Discouraging nudges

walls of the volume type that increases the volume of the wall to make corridors narrower. In the hospital activity, participants proposed using shape-changing walls of the type holes which closes to block movement in a certain direction. Another discouraging nudges ideas that occurred in the hospital activity include using shape-changing walls of the amplitude type which show cones that make route unpleasant and unattractive (See Figure 6.7 (b)) and using shape-changing walls of the waves type to indicate a stop (since it looks like TV static) and block movement in a certain direction.

6.6 Key Themes from the Interviews

At the end of the study, participants were asked to reflect on the VR experience, design activities as well as on the process as a whole.

6.6.1 Advantages and Disadvantages of Using VR

Participants discussed positive and negative aspects of their VR experience. In general, participants discussed how VR can be a great tool for prototyping products due to its low cost and short implementation time as well as allowing people to experience feelings towards the product that are close to the real experience. Also, participants contrasted 3D representations in VR to on-screen 2D representations and mentioned that 3D views in VR offer an immersive experience that allowed them to undergo emotional reactions that would not occur with 2D representations such as icons.

In addition, participants reflected on experiencing shape-changing walls in VR. Participants reported that VR have helped them in imagining and understanding the concept of shape-changing walls:*"that helped me to understand the concept of like changing walls or living buildings...it helped me to visualise and imagine how the environment and the wall could be"*(P15). P16 also mentioned that *"... without this, I would never have imagined the wall changing like that"*. In addition, participants discussed how VR have helped them in understanding how shape-changing walls affect emotions: *" I could really feel how I would feel if I was in that room or like at least I felt a lot more like I understand what it would be like to be there, than it would be if I just saw it on a screen. Um, yeah. So I think getting that emotion like understanding how intrusive it was and understanding how I feel when a wall is actually moving towards me. I think the VR was really important for that"* (P2). P5 also mentioned that the VR helped in understanding the emotional reactions of future users: *"It helped me imagine how future users of shape-changing walls might feel in an environment like that"* (P5).

Finally, several participants found the VR experience immersive, and reported that the sense of immersion enhances when all shape-changing walls of the room are activated: *"It feels quite a lot more immersive when you got peripheral stuff going on, kind of feels like you're within something rather than looking at something"* (P18).

In contrast, one participant reported that being in two worlds (real and virtual) at the same time affects immersion and makes it hard to be fully immersed in the VR environment. In addition, some participants showed some scepticism regarding particular shape-changing wall effects (e.g. volume, holes) in VR and mentioned that these effects were physically impossible and look unrealistic.

Additionally, participants also discussed difficulties they encountered during the VR experience. For example, many participants mentioned experiencing motion sickness which caused feelings of dizziness and nausea. Also, some participants found difficulties in controlling the movement in VR and reported that the type of movement control implemented (i.e. tilting head down to walk) made it difficult to see shape-changing walls while walking.

6.6.2 Design activities Benefits and Challenges

Many participants found the design activities "enjoyable" and "fun". P10 mentioned that*"... I wouldn't describe myself as a designer, but I felt like the activities helped me open up that design side of things in this particular context."*(P10). P11 was surprised to find that the on-screen design activities were successful and that it worked as a probe that encouraged people to talk.

However, some participants expressed that the design activities were challenging. For example, P15 mentioned that these difficulties come from the fact that he lacks imagination to design and that he is not good at drawing. P18 reported that such open design activities put more pressure on him as it requires one to be creative. Although the researcher provided continuous help to participants during the design activities, P9 mentioned feeling overwhelmed by the number of design parameters to think about and suggested using larger icons on the left or right of the screen rather than at the bottom.

6.6.3 The Overall Experience

Participants reflected on the whole VR and design experiences. Many of them found it engaging, fun and enjoyable. Participants also mentioned that the VR followed by design makes people more immersed with the design activities. One participant reported that she would have designed multiple times if possible.

From the discussions, the following points, which describe how the VR experience helped during the design activities, were identified:

1. *Understanding the concept of shape-changing walls and vocabulary needed for design:* Participants reported that this scaffolding process helped them understand the key concepts and vocabulary needed to design shape-changing walls. P11 mentioned that without the VR, thinking about the design of shape-changing walls would have been difficult: *"I think it would have been difficult to think about those kinds of shape-changing walls without having experienced it in some way"*(P11).

2. *Understanding how the different shape-changing walls types affect emotions and considering that during the design activities:* Participants mentioned that during the design activities, they were recalling how the shape-changing walls in VR made them feel and created their designs based on that: *"Feeling how certain ones made me feel definitely influenced my choice in the design activities"* (P20), *" I think thinking through the emotions I was feeling as I was viewing that helps me to think with the design activities"*(P17).

3. *Providing a concrete experience that is important for the design phase:* Participants expressed that the VR provided a realistic experience that helped during the design activities: *"VR was a really good way of kind of introducing, giving me some concrete experience and the ability to think about what the design parameters are"* (P11), while P12 mentioned that the VR was *"like living the real stuff"* and it would have been difficult to understand the parameters by, for instance, watching a video.

4. *Providing examples that acted as a frame of reference during the design activity:* Participants mentioned these clear examples are essential during design: *"VR provides a very vivid visual representation, especially the representation of a 3D structure, which is very important for anyone who wants to design a shape-changing display because the shape-changing display is a very visual thing"* (P19). Also, P6 reported that viewing the shape-changing wall examples in VR was helpful in knowing the level of fidelity needed during the design activities: *"I think just having the examples is really helpful, so kind of know to what fidelity I need to go into"* (P6)

5. *Inspiring the design outcomes and design of future buildings:* P2 explained that experiencing a particular type of shape-changing walls in VR inspired her during the design activity: *"When I saw that like blocks are moving out of the wall and back in again, I was like, oh, this really feels like I'm in an obstacle course and that kind of inspired me to do the design I did"* (P2). P17 mentioned that the inspiration that the VR experience provided extends to the design of future buildings: *" It gave me a lot of inspiration for thinking of future buildings design, just thinking of like how fun you can make buildings"* (P17). Other participants, however, reported that the VR experience inspired and shaped the design outcomes and that a different VR experience would result in different designs: *" I could have had different VR experiences which would have pushed me to think about other other kinds of ways of designing shape-changing interfaces or shape-changing buildings"* (P11).

6.7 Discussion

Shape-changing interfaces have been explored extensively in HCI [4]. Current explorations focus more on small-scale interfaces such as handheld devices(e.g. [162, 253]) and less on large-scale shape-changing interfaces. Although large-scale shape-changing interfaces have been developed and employed for various purposes such as information communication, ventilation [65] and as adaptive furniture [292], designing them to nudge, influence and guide navigational decision-making, due to their saliency, remains unexplored. In addition, existing large-scale shape-changing interfaces can be intrusive to move to the periphery of our attention and become ambient, hence, there is a need to understand how such large shape-changing interfaces can be embedded in our everyday life and become an architectural element of the building while being minimally-intrusive. Furthermore, since examining the design of shape-changing interfaces can be exceedingly difficult, prior work have explored the use of 2D video [228] and projected augmented reality [50] to investigate their design. These prior work have laid the foundation to study the design of shape-changing interfaces. I build on and extend prior work and propose using VR, which could offer immersive experiences that would allow exploring different designs of shape-changing walls and investigating their impact on people's perceptions and navigation decisions.

Experiencing large-scale shape-changing interfaces in VR has uncovered interesting insights into how shape-changing walls are perceived. With VR, participants were able to experience positive and negative emotional reactions and were able to report both induced and perceived emotions. Their emotional reactions ranged from feelings of excitement, pleasantness and clam to feelings of perceived anger and fear. Encountering this wide variety of emotions suggests that VR can be an effective tool for examining how large-scale shape-changing interfaces impact people's emotions. Prior work has examined Projected Augmented Reality as a platform for studying affordances of shape-changing interfaces and demonstrated that such a platform can help in studying their dynamic affordances. In this study, participants were able to detect different affordances of shape-changing walls in VR including, concrete affordances of action possibilities (e.g. sitting) and inviting/repelling affordances and hence, this suggests that VR can be a viable platform for uncovering the dynamic affordances of large shape-changing interfaces. Furthermore, it was surprising to find that participants were able to experience various sensory illusions while in VR. The movements that the shape-changing walls create made participants imagine hearing sounds and imagine experiencing changes in body temperature and body weight. Such sensory illusions occur as participants complete the missing parts of their perceptual experience by using a sensory cue of one modality [32]. These results are in line with prior work on sensory illusions in VR, which showed that people can experience different cross-modal illusions including, auditory-visual(e.g. [185]) and visual-haptic(e.g. [32, 327]. This confirms that VR is capable of inducing a wide range of sensory illusions to substitute the missing senses.

Although shape-changing walls are considered a salient technology due to their movement and changing qualities, this does not necessarily entail that they are always intrusive and visually-demanding. For such walls to blend with the environment and become an ambient technology that can move back and forth between the centre and periphery of attention as needed, they need to be designed as less or non intrusive. The findings showed that participants were able to design intrusive and non-intrusive shape-changing walls by manipulating the different shape-change parameters and identifying the ones (parameters) that make shape-changing walls intrusive or non-intrusive. For instance, participants suggested changing the type to Amplitude type to make the wall design more intrusive, whereas participants suggested changing the type to Curvature and Holes types to make the design less or non-intrusive. It is possible that this has occurred because of the sharp features used in the Amplitude type (i.e. cubes and cones) and the rounded edges used in the Curvature type. Previous work have showed that people tend to associate sharp shapes with toughness, strength and energy [30, 341] as well as threat and danger [23, 24], whereas rounded/curved shapes are usually associated with features that express friendliness and approachableness [30, 341]. In addition, participants proposed reducing the speed to make the wall design less or non-intrusive and increasing the speed to the design intrusive. These findings are in line with previous work on designing ambient technologies, which report that fast speeds are not suitable for ambient technologies as they are overly distracting and intrusive [56, 128]. Also, the findings showed that by reducing the scale (i.e. less walls are activated), shape-changing walls become less or non-intrusive and by increasing the scale, the walls design is considered more intrusive. This is because of the possible distraction and attentional demands that two or three walls would require compared to one wall. Furthermore, the findings showed that for the shape-changing wall design to be intrusive the type of interaction needs to be "no interaction", and for the design to be less or non-intrusive, the interaction type needs to be "direct interaction" or "indirect interaction". While there is no specific interaction type have been reported as appropriate for ambient technologies since prior work have used various types of interaction including no interaction (e.g. WaterLamp [337] and indirect interaction (e.g. Pinwheels [142]), it is essential for both interactive (direct and indirect) or not interactive technologies to not require too much from users [9]. A shape-changing wall that is changing continuously without giving the user the option to interact and stop it could be perceived as highly intrusive. Similarly, a shape-changing wall that demands too much interaction from the user can also be considered intrusive. A good balance is needed in choosing the type of interaction for such shape-changing walls to ensure that they can blend seamlessly with the surrounding environment. Moreover, participants suggested reducing the notification level to make the design of the shape-changing walls less or non-intrusive. For the abstraction level, the results show that reducing the abstraction level leads to intrusive shape-changing wall designs, whereas increasing it results in less or non-intrusive. These findings are in agreement with previous research on design dimensions of ambient technologies (which aim to design non attention-demanding/peripheral technologies), which report that high notification and low abstraction are considered intrusive and attention-demanding, while low notification level and high abstraction level are less intrusive [191, 227, 300, 337].

The saliency of the shape-changing walls can impact and nudge navigation decisions. The findings showed that shape-changing walls can be designed to impact navigational decision-making in two ways: encourage following a certain direction or discourage choosing a particular path choice. For example, participants chose to design shape-changing walls with the Waves, Curvature and Holes types to encourage people to follow certain directions and influence their navigational decisions, whereas walls were designed with the Amplitude type (showing cones or cubes) to discourage people from choosing a certain path choice. These findings are in conformity with past research discussed earlier that associate rounded shapes with approachability [30, 341] and angular shapes with a sense of threat [23, 24]. It is possible that the features of these shapes have affected participants' design decisions. Therefore, it is important for designers to consider the characteristics of each change type and choose a nudge (encouraging or discouraging) based on the requirements of the situation. For instance, to prevent museum visitors from going to a restricted area, shape-changing walls with Amplitude type (e.g. cubes) can be used, whereas to attract their attention and guide them towards a certain path choice walls with Waves type can be employed.

While the findings showed similar speed and scale settings to be used in both the art gallery and hospital, differences were found in change type for the two settings. For example, waves was the most frequently used change type on the art gallery, while the amplitude and holes were used most of the time in the hospital activity. It is possible that participants chose to design more direct types that explicitly inform individuals about a direction for a critical setting such as a hospital. However, in a fun setting (i.e. art gallery), the Waves type was chosen due to its aesthetic properties. Similarly, because of the characteristics of the hospital which requires immediate and quick actions, participants designed shape-changing walls with direct interaction most of the time, whereas in the less demanding setting such as the art gallery indirect interaction was used most frequently in designing walls.

Limitations A limitation of this study is using mobile VR rather than research-grade VR headsets (e.g. HTC Vive, Oculus) during the VR experience. This research was conducted during the COVID-19 pandemic, and because of this, there were many constraints related to carrying out face-to-face research and sharing research equipment. The best solution was to use mobile VR and send mobile VR viewers directly to participants from Amazon (without any contact with the viewer). Another limitation is conducting the VR experience and the design activities in a single session due to time constraints. It is possible that this might have resulted in participant fatigue, which might have affected the outcomes of the design activities.

6.8 Conclusion

In this chapter, I explored how supraliminal physical cues of shape-changing walls can be designed to impact navigation decisions with minimal intrusiveness levels. In an online study, I first used Virtual Reality to examine how people experience different types of shape-changing walls. Then, I engaged potential users in the design process of shape-changing walls that are minimally intrusive as well as walls that can influence and nudge navigational decision-making. Finally, I asked participants to reflect of the overall process. I gained new understanding of how shape-changing walls are perceived and how such walls can be designed to become ambient while also influencing navigation decisions within the built environment. In the next chapter, I use the design insights gained from this chapter in designing a study that evaluates the impact of four types of shape-changing walls on navigation decisions.

CHAPTER 7

Evaluating the Effect of Physical Cues on Navigation Decisions

THIS CHAPTER:

- Presents an online evaluation study in VR examining the impact of the designed salience nudge, which uses different types of shape-changing walls as physical cues, on navigation decisions.
- Describes how path choice behaviour is influenced by the different types of shape-changing walls and compares between them.
- Shows that the Zero-Crossing shape-changing walls type is well-suited to nudge and guide navigational decision-making towards certain directions while exploring indoor spaces.

7.1 Introduction

Chapter 6 showed that shape-changing walls can be designed to become an ambient technology that blends with the environment with minimal intrusiveness levels. Also, because of the saliency qualities that shape-changing walls possess, shape-changing walls can be used to influence and nudge navigational decision-making using the salience nudging mechanism. Chapter 6 particularly examined how such shape-changing walls can be designed to nudge navigation decisions and generated a number of shape-changing walls designs. However, the understanding of how such walls influence navigational decision-making and whether they can nudge people towards certain path choices remains limited.

Therefore, in order to understand how different types of shape-changing walls impact navigation decisions, I conduct an online evaluation study using mobile VR[1]. The study explores four designs of shape-changing walls which were produced in Chapter 6. These include Zero-Crossing, Amplitude, Concave Curvature and Convex Curvature. The study uses an updated version of the Living Building app developed in Chapter 6. Two main parts of the study were added in the updated Living Building app. The first part asks participants to explore a virtual art gallery containing corridors with shape-changing walls and plain corridors and explain the rationale behind the path choices they have made. This part was done for each of the four shape-changing walls types (i.e. four explorations of an art gallery). In the second part, participants examine all the four types together and as the gallery managers, they are asked to choose a suitable shape-changing walls type to install in the gallery in order to nudge and guide navigation decisions and to justify their choices. I present the findings and conclude the chapter with a discussion of them.

7.2 Method

The goal of this study is to examine the impact of the designed shape-changing walls on navigation decisions.

7.2.1 Participants

Twelve participants (5 female) took part in the online study, with ages ranging from 19 to 27 (M = 21.5 years old; SD = 3.08). Participants were university students (undergraduate and postgraduate) from different scientific disciplines. They were recruited via advertising emails sent to different university mailing lists. Five participants reported that they have no prior experience with VR. Three participants considered their experience level with VR as beginners and Four participants reported to have an intermediate experience level. Participants received a cardboard Virtual Reality Viewer as a compensation for their participation and to use during the study.

7.2.2 Experimental Design

A within-subject design was used with one independent variable with four levels: Type of shape change Zero-Crossing (creating a wave-like form), Amplitude (creating a number of cube shapes), Concave Curvature, Convex Curvature. The order of the types of shape change was counterbalanced with Latin-Square across participants.

[1]Mobile VR was used to avoid any contact with participants during the COVID-19 pandemic

Figure 7.1: The home page of the updated version of the Living Building mobile VR app.

7.2.3 Apparatus

An updated version of the Living Building VR mobile app (used in Chapter 6) was used, as shown in Figure 7.1. In addition to the Living Building rooms explored in Chapter 6, the home page of this updated version shows four buttons (*A*, *B*, *C* and *D*), each corresponding to a different type of shape change (Zero-Crossing, Amplitude, Concave Curvature, Convex Curvature). All these buttons direct the user to a room with three corridors (i.e. navigational choices), each with a number (1, 2 or 3) printed in a yellow colour on the floor (See Figure 7.2). The default position of the user is standing at the centre of these corridors while facing a wall with the sign "Look around". With buttons *A*, *B*, *C* and *D*, one of the corridors has shape-changing walls of one type of shape change, whereas the other two corridors have plain walls, as shown in Figure 7.3. The location of the shape-changing walls is randomised between corridors. Users can walk in any of these corridors and the app would direct users to the home page once they reach the end of it.

The updated version of the app also has a *Compare Types* button. This button directs the user to a room with four corridors. All corridors have a number in yellow printed on the floor (1, 2, 3 and 4). Each corridor shows one type of shape-changing walls, with Zero-Crossing type shown in corridor 1, Amplitude type shown in corridor 2, Concave Curvature shown in corridor 3, Convex Curvature shown in corridor 4 (See Figure 7.4). By walking through any of the corridors and reaching their end, the app ends the scene and directs the user to the home page of the app.

7.2.4 Procedure

The study was conducted online on Zoom and lasted on average 27 minutes. The study started by first welcoming the participant and giving an overview about the study, its parts and the data to be collected. Participants were then given instructions on how to interact with the mobile VR app using the VR viewer. Participants were asked to think aloud when answering questions and also describe what they see, any reactions or emotions. A number of checks were done before running the app. These include checking that the app has been installed with the latest update

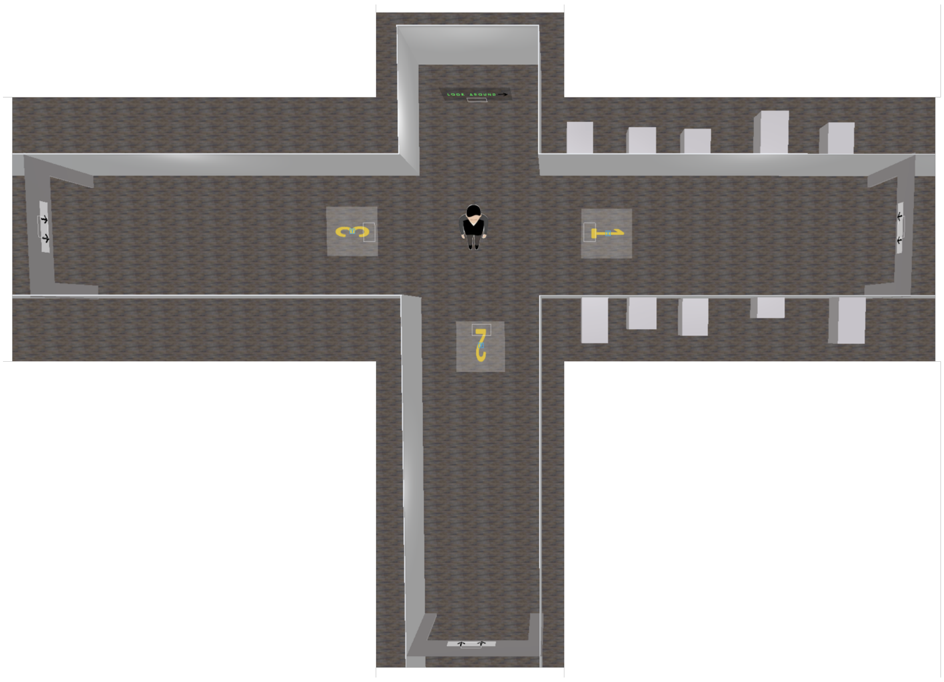

Figure 7.2: Top view of the room in button B of the Living Building app. It shows one corridor with an Amplitude shape-changing walls and two plain corridors while the participant is standing at the centre of these corridors.

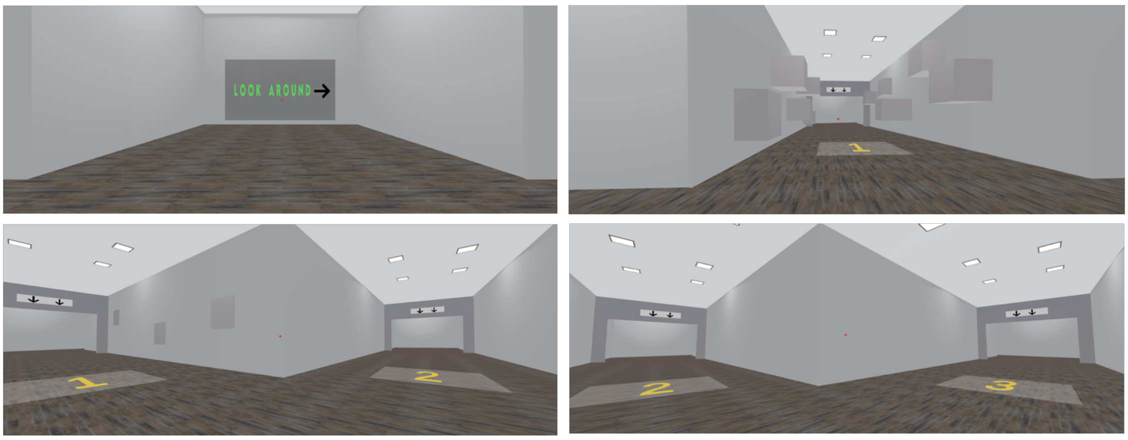

Figure 7.3: Participant's view of the virtual art gallery. Upon loading the scene, the participant is positioned to face a wall with "look around" sign. By looking around, the participant can see a corridor with an Amplitude shape-changing walls and two plain corridors.

and checking the brightness level of the phone and setting it to moderate brightness level.

Participants were then asked to run the app, wear the viewer and click on one out of four buttons *A*, *B*, *C* and *D* to start exploring one type of shape-changing walls. Once participants confirmed that they clicked on the button and entered the room, they were asked to look around 360° degrees without moving from the current position and to describe what they see. The researcher records which corridor has the shape-changing walls based on the participant's description. After that, participants are told that they are in an art gallery and were asked to select which path choice would they choose to explore it and why. Then, participants were asked whether they had noticed the shape-changing walls and if so, they were asked to describe how the shape-changing walls make them feel when standing at the default position (i.e. centre) as well as when walking towards the corridor with the shape-changing walls and being in the middle of it. Participants were then asked to walk in the corridor they selected and to reach the end of it (See Appendix E for the scenario and questions). The mobile app returns the participant to the home page after finishing exploring the first type (first button). Participants were then instructed to click on the next button (based on the Latin-Square counter-balancing) to start exploring another shape-changing walls type. This continued until participants completed exploring all four types of shape-changing walls in buttons *A*, *B*, *C* and *D*.

Finally, after completing exploring the four types of shape-changing walls, participants were asked to click on *Compare Types* button. Then, participants were instructed to look around 360° and to describe what they see. After that, participants were asked to imagine that they are managing this art gallery and were asked to think of which wall (out of the four walls) to install in the gallery in order to nudge people to follow certain directions, and to explain their reasons behind their choices. Participants were then asked to walk in the corridor they selected and reach the end of it (See Appendix E for the scenario and questions). Then, the app directs the user to the home page of the app. Participants were then informed that this is the end of the study and were thanked for their participation.

7.2.5 Data Collection and Analysis

The study was audio-recorded and notes of participants' answers were taken. Audio-recordings were automatically transcribed using an online transcription tool. Transcription files were cross-checked with the audio files to check for any errors made by the automatic transcription (e.g. incorrect or missing words).

The frequency of navigational choices within each examined type of shape-changing walls was analysed. An inductive thematic analysis was used to analyse participants' reasons behind their choices and their feelings and thoughts of the different shape-changing walls types. These qualitative data were first read and openly coded. Peer validation [5] was then conducted throughout the coding process with an additional researcher to review and clarify codes and emerging themes.

NVivo, the qualitative data analysis software, was employed to code the qualitative data. All codes were then moved to Miro [1], which is an online collaborative whiteboard platform, to collaborate with the research team in conducting the thematic analysis.

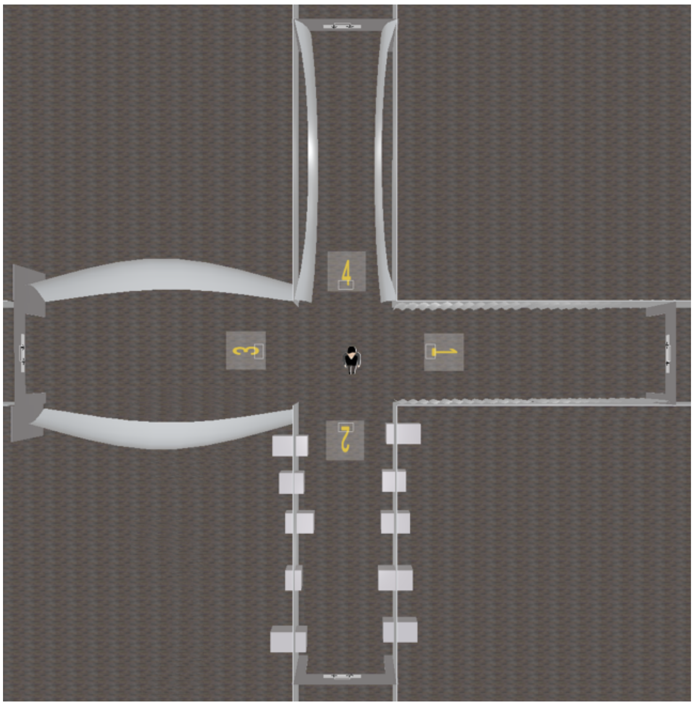

Figure 7.4: Top view of the Compare Types button in the Living Building app. It shows the Zero-Crossing type in corridor 1, Amplitude type in corridor 2, Concave Curvature type in corridor 3 and Convex Curvature type in corridor 4.

7.3 Results

In this section, I present the findings of the path choices, the frequency and the rationale behind participants choices. Also, I present the frequency and justification of selected shape-changing walls types to nudge navigation decisions.

7.3.1 Frequency of path choices

The frequency of path choices in each of the four rooms containing shape changing walls was analysed, as shown in Figure 7.5. To explore the art gallery containing shape-changing walls of the Zero-Crossing type, about 92% (n=11) of participants selected the path choice with the shape-changing walls and only around 8% (n=1) of participants explored the art gallery by choosing a plain corridor. 75% (n=9) of participants chose the path choice containing shape-changing walls of the Amplitude type and around 25% (n=3) selected either one of the plain corridors, when asked to explore this art gallery. In the Concave curvature art gallery, around 83% (n=10) of the participants chose to the explore it by selecting the path choice with the shape-changing walls and only about 17% (n=2) of participants chose either one of the plain corridors. About 58% (n=7) of participants chose to explore the Convex Curvature art gallery by selecting the path choice with shape-changing walls, whereas around 42% (n=5) of participants selected either one of the other plain corridors.

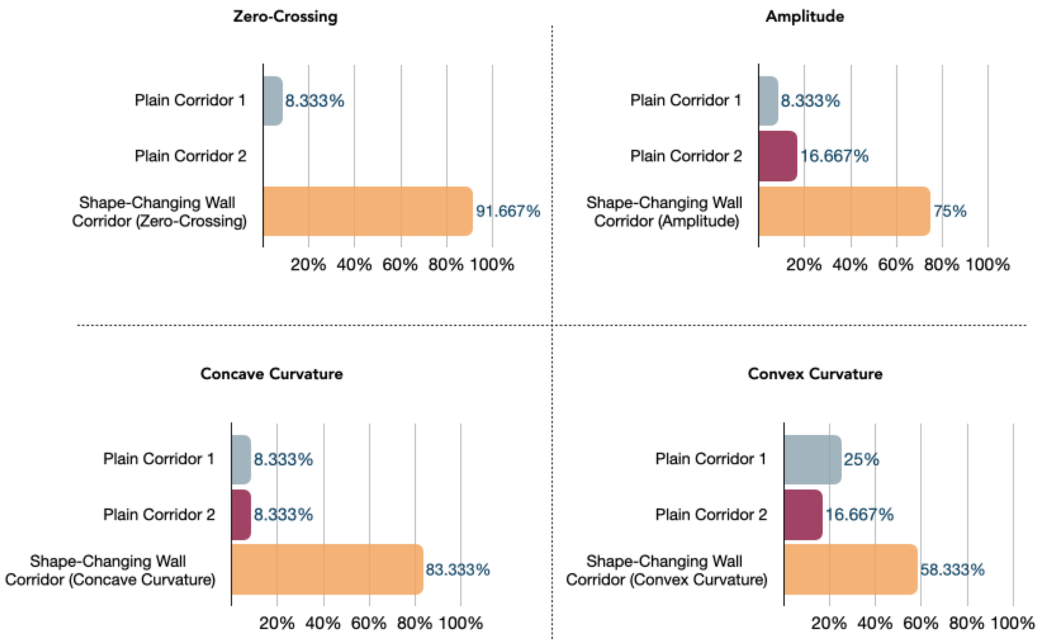

Figure 7.5: Frequency of path choices made by participants in four types of shape-changing walls including, Zero-crossing, Amplitude, Concave Curvature and Convex Curvature.

7.3.2 Rationale Behind Participants' Path Choices

The rationale behind participants' path choices was analysed using thematic analysis. Four main themes were generated: 1) Triggering Emotional Responses; 2)Arousing Interest and Curiosity; 3) Examining Physical Qualities; 4) Making Connections to Living and Non-living Things.

Theme 1: Triggering Emotional Responses

Participants described how they felt when they were asked to explain why they chose a particular path choice. Participants expressed emotions of both fear and happiness. For example, participants described feelings of fear caused by the Amplitude type (i.e. showing cubes) as it can harm them: *"There are chances that it would come out further and hit you"* (Amplitude, P1), *"The squares coming out of the walls, I feel like I might be squished or something"* (Amplitude, P10). Also, P7 expressed that the Convex Curvature type is *"...more intimidating.....they could burst out towards you at any time, it seems less controlled"* (Convex Curvature , P7). In addition, participants described that the Zero-Crossing and Concave Curvature were not threatening: *"It doesn't look threatening"* (Zero-Crossing, P12), *"I like the openness of it, it's moving outwards so it's the least threatening"* (Concave Curvature, P11).

Furthermore, participants expressed feelings of happiness when asked to describe their rationale behind their choices. For instance, P7 described that he would choose the corridor with the shape-changing walls because: *"it's the most exciting"*(Zero-Crossing, P7). Similarly, P8 reported that she would select the shape-changing wall corridor as *"it feels like there's a lot of* *energy in that direction."* (Concave Curvature, P8). Participants also explained that their choices were because of a sense of calm they felt towards the shape-changing walls: *" the ripple effect is like quite calming but also like interesting"* (Zero-Crossing, P10), *" movement is peaceful"* (Concave Curvature, P8).

Theme 2: Arousing Interest and Curiosity

Participants explained that their choices were because shape-changing walls sparked curiosity and interest in them. For example, participants described that: *"the walls are interesting"* (Zero-Crossing, P2), *"The bending kind of aesthetic is interesting"* (Concave Curvature, P6). P8 mentioned that the cubes in the Amplitude type *"have sparked my curiosity"* (Amplitude, P8) and that is why she chose the corridor with the shape-changing walls. P9 compared the corridor with the shape-changing walls with the other plain corridors and explained that the plain corridors: *"seem to just be kind of standard, whereas number one* (referring to the corridor with shape-changing walls) *seems to have something fairly strange going on down there so curiosity calls that I have a look"* (Convex Curvature, P9).

Participants mentioned perceiving an inviting effect from the shape-changing walls, which explains their rationale behind their path choices. For instance, P8 described that the shape-changing walls: *"lures you in, the moving walls they kind of promise something exciting at the end"*(Amplitude, P8). P6 expressed that he chose the corridor with the shape-changing walls to explore the art gallery because it might lead to shape-changing art: *"The walls are kind of shifting so it makes me think that the arts in there are all about shifting reality"* (Convex Curvature, P6). P1 explained that she would rather choose to explore the art gallery by following one of the plain corridors instead of the corridors with the shape-changing walls in the Concave Curvature and Convex Curvature as they are: *"uninviting"* (Concave Curvature and Convex Curvature, P1).

Theme 3: Examining Physical Qualities

Participants reported that the physical qualities of the corridors made them prefer choosing a particular corridor to explore the art gallery more than the others. For instance, participants expressed that they chose the corridor with the Concave Curvature shape-changing walls because it made the space larger: *"It looks bigger like more space, if I was in an art gallery I'd want to go to the biggest bit first"* (Concave Curvature, P10), *"I like how the room is becoming larger"* (Concave Curvature, P9). P5 reported that not feeling a change in corridor dimensions made them select that corridor to explore the art gallery: *"I don't feel space change"* (Zero-Crossing, P5). P8 justified her choice of exploring the art gallery by choosing one of the plain corridors by comparing the space changes in the Concave Curvature and Convex Curvature: *"I think that one was bending outwards, this is the opposite, bending inwards, so the one before was giving you more space then going back to normal, whereas this one is taking away space"* (Convex Curvature, P8).

In addition, participants expressed that the distinctiveness of the corridors with the shape-changing walls compared to the plain corridors made them select their path choices. For example, P2 and P6 explained that they would choose the corridors with the shape-changing walls because they are different and unique compared to the other corridors: *"Number two (referring to the corridor with the shape-changing walls) really just because it's different"* (Convex Curvature, P6), " *because it is that the one that is different versus the other two are the same, so I probably go to the one that's unique"* (Concave Curvature, P2).

Theme 4: Making Connections to Living and Non-living Things

Participants justified the reasons behind their path choices by making connections to biological processes of living things as well as making connections to non-living things. For example, P4 reported that the corridor with the Concave Curvature shape-changing walls felt more alive compared to the others: *"it's more alive, it feels alive in a way"*(Concave Curvature, P4). Also with the Concave Curvature shape-changing walls, participants used biological processes to explain why they chose the corridor with the shape-changing walls: *"The wall looks like it is breathing"* (Concave Curvature, P4), *"seems like the room has a heartbeat"* (Concave Curvature, P8). P10, however, found that the breathing effect made him choose one of the plain corridors to explore the art gallery: *"I don't think I would go down it because it looks like the walls are like breathing"*(Concave Curvature, P10).

Additionally, P10 justified his path choice by making connections to real-world objects: *"because it does remind me of theatre curtains how they're huge and got that kind of folds in them"* (Zero-Crossing, P10).

7.3.3 Frequency of shape-changing wall types to nudge navigation decisions

Participants compared the four shape-changing walls types: Zero-Crossing, Amplitude, Concave Curvature and Convex Curvature in order to choose a suitable type that can be used to nudge people towards certain directions and influence their navigation decisions. The frequency of participants choices was analysed, as shown in Figure 7.6. Two participants chose two types of shape-changing walls and considered them both as suitable to nudge navigation decisions, whereas all the other participants selected one type of shape change. When participants select two types as their choice, the count is divided between the two types. In this case, to calculate the frequency of choices of each participant, a count of 0.5 is given for the first type and a count of 0.5 is given for the second type, rather than a count of 1 for selecting one type.

Most participants (75%, n=9) considered the Zero-Crossing type as the most suitable type to nudge navigational decisions compared the other types. Around 12.5% (n=1.5) of the participants chose the Concave Curvature and about 8% (n=1) selected the Convex Curvature as the shape-changing wall type that can be used to influence navigation decisions. Only 4% of participants selected the Amplitude types as a type of shape-changing wall that can nudge people towards particular direction and impact their navigation decisions.

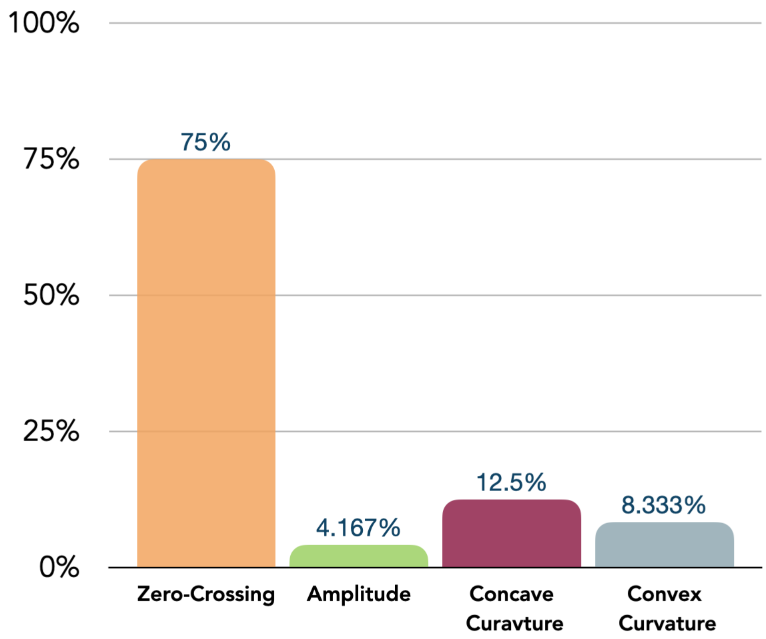

Figure 7.6: Frequency of choices made by participants of the suitable shape-changing wall type that can be used nudge and guide navigation decisions.

7.3.4 Justification of chosen change type to nudge navigation decisions

Participants described their reasoning behind considering a particular type suitable to nudge navigational decisions while other types are not. These reasons were thematically analysed and four themes were generated: 1) Provoking a Sense of Pleasantness/Unpleasantness; 2) Influencing Feelings; 3) Conveying an affordance; 4) Changing Space Dimensions.

Theme 1: Provoking a Sense of Pleasantness/Unpleasantness

Participants expressed that certain types of shape-changing walls bring a sense of pleasantness and hence they can be used to nudge people to follow certain path choices within an art gallery. For example, participants mentioned that they considered the type suitable to nudge navigation decisions because it looked *"cool"* (Concave Curvature, P8), *"fun"* (Amplitude,P12), *"nice"* (Zero-Crossing, P1). Also, participants explained that particular types are unpleasant and that they would avoid choosing them to influence navigation decisions within an art gallery. For instance, P10 mentioned that the Concave Curvature shape-changing wall: "*strains your eyes a bit just to look at it*"(Concave Curvature, P10), whereas P11 reported the the Zero-Crossing type is: *"a bit too plain, too repetitive"* (Zero-Crossing, P11).

Theme 2: Influencing Feelings

Participants explained that particular types of shape-changing walls can be used to nudge navigation decisions as they can influence people's feelings. For instance, participants described that the Zero-Crossing can be appropriate to influence navigation decisions as it is: *" very peaceful....It makes you feel calm"*(Zero-Crossing, P8), *"The wave effect has a little bit of a calming effect, it puts people at ease"*(Zero-Crossing, P9). Participants also reported that certain types of shape-changing walls would not be suitable to impact navigation decisions as: *"They can be a bit distressing"*(Concave Curvature and Convex Curvature, P9). P6 described how scary the Amplitude type would be and hence he would not consider it as a shape-changing wall to nudge navigation decisions: *"You got kind of big slabs of wall kind of pushing in and out where it would feel almost kind of scary to walk through"* (Amplitude, P6).

Theme 3: Conveying an affordance

Participants explained that certain types of shape-changing walls express an inviting affordance, and thus are suitable to nudge navigational decisions within an art gallery. For example, participants mentioned that particular types are:*"inviting"* (Zero-Crossing, P1), *"more enticing than the others"* (Concave Curvature, P3). P9 expressed that she feels that the shape-changing wall of the Zero-Crossing type can be suitable as it is encouraging her to take that corridor: *"I feel like i'm getting the effect that it's encouraging me to walk down this corridor"* (Zero-Crossing, P9). In addition, participants described that they chose the Zero-Crossing type because it gives: "a sensation of motion in a certain direction" (Zero-Crossing, P2) and that the shape change guides people's navigation decisions: *"the pattern that's like you should follow it and that's the direction you should be going"*(Zero-Crossing, P1). P6 explained that certain types of shape-changing walls are not appropriate to nudge navigational decisions because they are: "Very uninviting" (Amplitude, P6). Also, participants described that shape-changing walls that do not provide a feeling of motion in certain direction are not suitable to nudge navigational decisions:*"it doesn't really give me any kind of sense of forward motion"*(Concave Curvature, P6).

Theme 4: Changing Space Dimensions

Participants explained their reasoning behind their choice of a shape-changing wall type that can influence navigation decisions by describing changes in space dimensions (e.g. space is getting bigger or smaller). For instance, P5 described why the Concave Curvature would be suitable to nudge navigation decision: *"it makes me have more space"* (Concave Curvature, P5). Participants also justified not choosing a particular type because it makes spaces smaller: "constricting" (Convex Curvature, P10), "I think the cube wall is making the space smaller" (Amplitude, P5).

7.4 Discussion

Due to their saliency, large-scale shape-changing walls can have the ability to bias people's navigational decisions during the exploration of novel environments [250, 317–319]. Such walls have been designed to become ambient and blend with the surrounding environment with minimum intrusiveness levels (See Chapter 6). Also, they have been designed to nudge navigational decision-making and guide people towards certain directions within an indoor setting (See Chapter 6). However, the resulting designs have not been evaluated yet and it remains unknown how different types of shape-changing walls impact navigational decision-making. This study examines these designs in an online evaluation study in VR in order to understand how different types of shape-changing walls influence navigation decisions.

The findings showed that most people prefer to explore the art gallery by choosing the path choices that have shape-changing walls. This was expected because of the salient qualities of the shape-changing walls. These results are in line with prior work showing how salient environmental features impact navigational decision-making [319]. While the impact of shape-changing walls on directing people towards them was evident, it occurred in some types more than the others. For example, with Zero-Crossing and Concave curvature more than 80% of participants chose the corridor with the shape-changing walls. However, the percentage of participants who chose the corridor with the shape-changing walls was lower in the Amplitude and Convex Curvature. It is possible that these findings occurred because of a perceived sense of fear or perceived space changes, which resulted in a repelling effect rather than an attraction influence.

Participants expressed various reasons to explain their rationale behind the path choices they selected to explore the art gallery. These justifications show that shape-changing walls can have a wide range of effects on people and this as a result can influence how would people make their navigation decisions. For instance, the sense of happiness that people would perceive from the shape-changing walls attracts people towards the path choice containing shape-changing walls, whereas feelings of anxiety and panic deter people from selecting path choices with shape-changing walls (particularly the Amplitude and Convex Curvature types). In addition, participants explained that interest curiosity in the shape-changing walls would attract them towards the path choice with shape-changing walls. These findings are with agreement with previous work which reported that elements of the environment that invoke curiosity can influence navigation decisions [250]. Furthermore, participants reported a preference towards selecting path choices with shape-changing walls that make corridors bigger, which is in line with prior work which reported a preference of wider corridors during an indoor navigation task in VR [318]. With the Concave Curvature shape-changing wall, participants used biological processes to explain their path choice of the corridor with the shape-changing walls, whereas in the Zero-crossing type, participants used a description of *"curtains"* to explain their rationale. It is possible that the familiarity of such processes and real-world objects made participants more comfortable choosing the path choices with the shape-changing walls.

As managers of the art art gallery, most participants chose to install the shape-changing wall of the type Zero-Crossing to nudge people within the gallery to follow certain path choices.

Positive descriptions were used frequently by participants to justify their choice of the Zero-Crossing type. For instance, it was described as pleasant, calm, peaceful, inviting and directional. Hence, these features make the Zero-Crossing shape-changing wall *well-suited* to nudge and guide navigational decision-making towards certain directions while exploring indoor spaces (e.g. museum, gallery). Although some of the other scw types (e.g. Concave Curvature) were also positively perceived in terms of the pleasantness, spaciousness and affordance they provide, comparing this type with the Zero-crossing type and how it influences feelings makes it less preferable as they can be anxiety-inducing.

Limitations One limitation of this study is the focus on qualitative data to understand such a decision-making process. Although this can limit our understanding of the influence of shape-changing walls on navigation decisions, it provided, as a first step, useful insights into their impact on navigational decision-making. Another limitation is the use of plain corridors during the first set of scenarios (in buttons A,B,C and D) and comparing it to corridors with shape-changing walls. While this might result in bias when making navigation decisions, the collected qualitative data provided a deeper understanding of participants' rationale which helps in discovering and examining such bias.

7.5 Conclusion

In this chapter, I examined the influence of the physical cues of shape-changing walls on navigation decisions. In an online study in VR, I evaluated four types of shape-changing walls and investigated how they can impact navigation decisions. I gained novel insights into the influence of different types of shape-changing walls on navigational decision-making. In the next chapter, I present a general discussion of the work presented in this thesis by bringing together findings from this and previous chapters.

Chapter 8

Discussion and Conclusion

THIS CHAPTER:

- Summarises research findings described in the previous chapters and answers the research questions.
- Highlights contributions to knowledge.
- Discusses directions for future work.

In this thesis, I explored how ambient technologies can be utilised to guide and nudge navigational decision-making implicitly while carrying out a primary task, i.e. exploring an indoor environment. I started by examining whether and how a low cue level (i.e. subliminal cue) that falls below the threshold of conscious perception could influence decision-making. Such subliminal cues can communicate and deliver information without negatively affecting the user's main task. The findings of the preliminary study examining subliminal cues showed inconsistencies in the influence of subliminal cues on decision-making, which would make their use in various applications particularly challenging, and hence I concluded that such cues are not be suitable for ambient technologies.

These findings have led to exploring a higher cue level (i.e. supraliminal cue), which uses a perceptible cue that affects decisions without awareness, to influence decision-making. These cues can be delivered through the nudging approach, which takes advantage of the cognitive biases that humans have to influence their behaviours. Since this thesis focused on navigational decision-making, I examined the wayfinding literature and identified two cognitive biases that people use to facilitate their navigational decision-making: Social norms bias and salience bias. In thesis thesis, I used the corresponding nudging mechanism (i.e. Social Norms mechanism and Salience mechanism) and the supraliminal cues they use in understanding whether nudging as an approach can be used to influence navigational decision-making. In particular, I studied these mechanisms and their cues and investigated how technologies that utilise these mechanisms can be designed. Then, I evaluated the impact of the designed technologies on navigational decision-making. These empirical studies have provided novel insights into understanding, designing and evaluating ambient technologies that nudge navigation decisions.

The insights gained from the work conducted in this thesis can be used to provide seamless navigational guidance within public spaces (e.g. museums) that do not impact people's primary task of exploring spaces. These insights can also be used in organising the circulation and flow of visitors in public spaces, which plays an essential role delivering a complete visitor experience. Also, we have witnessed many ways to control the flow of people during the COVID-19 pandemic including, asking people to follow certain directions and using one-way system. Hence, The insights provided by this thesis can be used in such situations where navigation decisions are influenced in an unobtrusive way.

In this concluding chapter, I revisit the research questions set at the beginning of this thesis, list my contribution to knowledge and discuss directions for future work.

8.1 Answering the Research Questions

The main research question that was addressed in this thesis was:

How can ambient technologies be utilised to unobtrusively facilitate, guide and nudge navigational decision-making while exploring indoor spaces?

To answer this question, this thesis addressed the following sub-questions, which have been answered by the findings of the empirical work conducted in this thesis. Below, I discuss the answers to these sub-questions.

RQ1: *To what extent can the priming mechanism that employ subliminal cues (i.e. presented below the threshold of conscious perception) be used to influence decision-making and be used in ambient technologies?*
This question was addressed by carrying out an empirical study investigating the feasibility of the subliminal priming mechanism (See Chapter 3). I particularly examined the subliminal priming mechanism with peripheral subliminal cues (i.e. cues presented at peripheral visual angles) which would allow exploring whether such cues can be embedded in ambient technologies. The study also explored three types of subliminal cues and whether they are effective at influencing decisions when presented using two presentation durations. The study showed that using the subliminal

priming mechanism with peripheral cues is not suitable for use in ambient technologies. This is because of the inconsistencies in the findings which demonstrated that specific types would only be effective at influencing decisions if presented at a specific visual angle and with a specific presentation duration. For instance, the word stimulus can be effective at influencing decisions if presented at +15° with a presentation duration of 33ms, but this stimulus can not be used if presented at a visual angle of -15°. These findings make the use of peripheral subliminal cues in ambient technologies particularly challenging.

Although prior work have shown that the subliminal priming mechanism can influence decision-making(e.g. [52, 60]), these previous explorations have focused on central presentations of the cues (i.e. subliminal cue is presented at the centre of the screen and the user is asked to focus on that central location). However, in ambient technologies, where the reliance on peripheral communication is high, such central presentations would not be suitable as they would result in interruption of the primary task. Although the subliminal stimulus cannot be perceived due to its short presentation duration, the mask that follows and/or precedes the subliminal stimulus; which is important to ensure that the visual buffer has been overwritten [82], could be perceived as they are presented using a longer presentation duration compared to the subliminal stimulus [25].

RQ2: *Can nudging with overt cues (i.e. supraliminal cues) be used as an approach to influence and guide navigational decision-making in ambient technologies?*
Nudging approach can be used to influence and nudge navigational decision-making. By examining two cognitive biases (i.e. social norms bias and salience bias) that people employ to facilitate their navigational decision-making, I showed how the corresponding nudging mechanism and the supraliminal cues (social and physical cues) that it uses can influence decision-making. To do so, I first gained an understanding of the cues used by the nudging mechanisms and how they affect perceptions(See sections 4.3 and 6.4). Following that, I engaged participants in designing ambient technologies within each of the nudging mechanism studied (See sections 4.4 and 6.5). Based on the design activities outcomes, I carried out evaluation studies to examine the impact of the designed technologies and the cues they use on navigation decisions (See Chapter 5 and Chapter 7). Within this research question (RQ2), there are sub-questions that examine the aforementioned aspects in more depth. The findings of the empirical studies answer these sub-questions, as explained below:

RQ2.1: *How can ambient technologies be designed to influence navigational decision-making through nudging mechanisms?*
Each of the studies described in Chapter 4 and Chapter 6 show that different forms of ambient technologies can be designed to influence navigational decision-making using two different nudging mechanisms. In each of the preceding chapters, I first provided an understanding of the space and how such technologies impact people's perceptions through interviews (See Section 4.3) and by involving participants in a virtual reality experience (See section 6.4), which has

aided the following design step. Then, I provided insights into how such ambient technologies can be designed to influence navigation decisions using two nudging mechanisms by engaging participants in design activities.

Prior research on wayfinding have shown that people have a tendency to follow other people or their traces as a way to facilitate their navigational decision-making (i.e. social norms bias) [77]. This bias can be leveraged by the corresponding nudging mechanism (i.e. social norms mechanism) in order to influence and change navigation decisions. In Chapter 4, I proposed the use of floor interfaces as a platform to deliver such a nudge, since they are considered an ambient technology as they are an architectural element that can blend with the environment and can move back and forth between the centre of attention and the periphery as needed. As shown in prior work [207], interactive floor interfaces are considered suitable to deliver traces of other people, which I referred to as *social cues*. Such social cues were used to nudge and influence navigational decision-making. In the first study in chapter 4, I gained an understanding of the space by exploring how these social cues can be visualised, how they impact navigation decisions when presented on the floor and how they are interpreted, in a mock-up setting (i.e. large projected display of two path choices). The findings showed that direct and intuitive visualisations such as footprints are preferable to represent traces of other people. The study also identified a number of challenges in designing such history-enriched floor interfaces. For example, how such floor interfaces can represent multiple people in the same space and whether social cues would go unnoticed if presented on the floor.

The second study in Chapter 4 engaged potential users in design activities that address these design challenges. An interactive floor interface was implemented and used as a probe during these design sessions. The findings showed how such floor interfaces can be designed to incorporate social cues that influence navigation decisions in real-world settings. For instance, participants proposed using footprints with different colours, patterns and sizes rather than using unified footprints in order to represent multiple people in the same space. Such realistic features could be more effective at influencing navigation decisions compared to the unified footprints design. In addition, participants proposed incorporating non-identifying information about previous people within the floor social cues such as age and interests, which can also result in a stronger impact of social cues on navigational decision-making compared social cues showing only direction of movement. Finally, I identified a number of design dimensions to help designers in designing history-enriched floor interfaces.

People tend to depend on salient and attention-grabbing items when making their navigation decisions [250, 317–319]. The salience nudging mechanism can utilise this salience bias in order to influence and nudge navigation decisions. One way to nudge and influence navigational decision-making using the salience mechanism is to add a contrasting perceptual quality such as movement within path choices. In Chapter 6, I proposed the use of shape-changing walls, as they possess such salience quality. The online study allowed participants to first experience various types of shape-changing walls in VR before engaging them in the design process, in order to gain an understanding of the space and how shape-changing walls affect people's perceptions. The VR experience have resulted in many interesting insights into the impact of shape-changing walls on people's perceptions. For instance, shape-changing walls caused a wide range of positive and negative emotional reactions including feelings of fear, happiness and serenity. In addition, participants uncovered many affordances that shape-changing walls convey including, concrete affordances such sitting and inviting affordances. Also, by experiencing shape-changing walls in VR, participants experienced pleasant and unpleasant sensory illusions such as hearing sound and feeling changes in body temperature. In addition to the gained understanding that would inform future shape-changing walls designs, the VR experience helped participants understand the vocabulary needed in the following design step.

The second part of the online study presented in Chapter 6 involved future users in designing shape-changing walls that are non-intrusive so they can become ambient and move to the centre of attention only when needed as well as designing them to influence and nudge navigation decisions. The co-design sessions provided useful insights into the design of shape-changing wall in these two aspects. For example, the findings showed that certain types of change such as Amplitude and speed setting of fast can make designs more intrusive than others. In addition, shape-changing walls can be designed to either encourage or discourage choosing a certain path choice. For instance, to design a shape-changing wall with an encouraging nudge, Zero-Crossing (showing a wave-like shape) or Curvature types can be used. However, types such as Amplitude (showing cones or cubes) can used to design shape-changing walls with a discouraging nudge.

RQ2.2: *How do ambient technologies designed using nudging mechanisms influence navigational decision-making?*

Ambient technologies designed using the social norms (See Chapter 4) and salience (See Chapter 6) nudging mechanisms affect navigational decision-making in many ways. In each of the empirical studies examining the influence on navigation decisions (Chapter 5 and Chapter 7), I provide insights into how the designed technology influenced navigational decision-making.

Social cues, displayed as footprints on an interactive floor display, can impact navigation decisions. Qualitative findings from Chapter 5 showed that this impact depends on how participants in the intervention condition interpreted the cues. For instance, some participants preferred to follow popular paths (showing a number of social cues), whereas others avoided busy and crowded paths and preferred to take unexplored paths. This indicated that the impact of the social cues is not limited to attraction and nudging towards a certain path choice, but it can also deter people from following particular paths while exploring indoor environments. Additionally, by observing behaviours of participants while carrying out the tasks, I found a pattern of direct behaviours and less hesitation and stops in the intervention condition, and less direct behaviours and more hesitations in the control condition, which suggests that social cues can, to a certain extent, influence and nudge navigational decision-making while exploring spaces. Nonetheless, it is essential for designers to consider both viewpoints (i.e. social cues can attract, social cues can deter) when using such floor interfaces.

The physical cues that the Shape-changing walls deliver can affect navigation decisions. Results from Chapter 7 showed that the majority of participants preferred to explore the art gallery by choosing path choices with shape-changing walls. Although this was expected due to their saliency, it occurred in particular types more than others. The used type of change added another layer to the saliency quality of the shape-changing walls. For instance, corridors with Zero-Crossing and Concave Curvature shape-changing walls types were selected by more than 80% of participants, whereas the corridors with the Amplitude and Concave Curvature types were chosen less compared to the Zero-Crossing and Concave Curvature. When participants described their rationale behind the path choices they made, it was clear that the different shape-changing walls types affect people and their choices in several ways. For example, path choices with shape-changing walls types that trigger emotional reactions such as sense of threat and fear (e.g. Amplitude) deter people from following that path choice, whereas path choices with shape-changing walls types that trigger a sense of calm (e.g. Zero-Crossing) attract people towards them. Also, findings showed a preference in selecting path choices with types that make corridors wider (e.g. Concave Curvature). By assessing and comparing four types of shape-changing walls, I found that the designed Zero-Crossing type is well-suited to influence navigational decision-making in indoor public environments.

8.2 Contributions

I have contributed new knowledge to the field of HCI while responding to the research questions set in this thesis. Here, I restate the contributions of this work.

Chapter 3 provided a new understanding into the use of peripheral subliminal cues to influence decision-making and whether these cues can be used in ambient technologies. By examining three subliminal stimulus types shown at thirteen visual angles and presented using two presentation durations, I demonstrated that, while particular types of subliminal stimulus can significantly impact decision-making when presented at specific visual angle, peripheral subliminal cues are not suitable for impacting decision-making in ambient technologies. This is because of the inconsistencies in the findings that would make embedding such cues in any practical application for ambient technologies challenging.

Chapter 4 and Chapter 6 presented an understanding of the use of two nudging mechanisms (Social Norms nudge and Salience Nudge) and how the cues they employ affect people's perceptions. I provided insights into how social cues can be visualised, how they impact navigation decisions when presented on the floor and how people interpret them in Study 1 (Chapter 4). I showed that direct and intuitive visualisations (i.e. footprints) are well-suited to represent traces of other people. In the VR experience of Chapter 6, I provided a novel understanding into how physical cues of shape-changing walls impact people's perceptions. I demonstrated that shape-changing walls can impact people in many ways including, provoking emotional reactions and inducing sensory illusions.

In Chapter 4 and Chapter 6, I provided guidelines and design recommendations for designing ambient technologies that influence navigational decision-making in two nudging mechanisms. In Study 2 in Chapter 4, I provided a set of guidelines for designing history-enriched floor interfaces that influence and nudge navigation decisions. I demonstrated that using realistic visualisations of in the design of such floor interfaces is preferred. In addition, the design activities in Chapter 6 have resulted in useful insights into designing shape-changing walls with minimal intrusiveness levels as well as insight into designing them to impact navigational decisions. I showed that using certain types of change can makes designs more intrusive. Also, I demonstrated that shape-changing walls can be designed to nudge navigation decisions by using encouraging nudge designs and discouraging nudge designs.

Chapter 5 and Chapter 7 provided an evaluation of the impact of the designed ambient technologies on navigational decision-making. Chapter 5 have provided a new understanding into how social cues, presented as footprints on an interactive floor interface, impact navigation decisions. I showed that the impact of social cues on navigation decisions depends on how the cues are interpreted. Chapter 7 presented novel insights into the effect of different types of shape-changing walls on navigational decision-making. I demonstrated that certain types of shape-changing walls can attract people into taking path choices with shape-changing walls, while other types can deter people from following them.

8.3 Directions for Future Work

The work conduced in this thesis opens up a number of directions for future work. Here, I discuss these future directions.

Design Space This thesis examined two nudging mechanisms (Social Norms and Salience), which have been identified based on cognitive biases from prior wayfinding research. Previous work have also showed that there are a number of other cognitive biases that people employ to facilitate their navigational decision-making (See Section 2.2.3). For instance, the affect bias [274], which occurs when people rely on emotions rather than available information to make decisions, is used when making navigation decisions that involve sound and odours [16], since such sensory cues impact emotional responses [36, 197]. This bias can be leveraged by the corresponding nudging mechanism (i.e. Affect). Technologies that employ this mechanism can be designed and utilised in guiding navigation decisions in indoor environments. Future work should explore additional mechanisms and how technologies can be designed to deliver them. In addition, this thesis explored one way of expressing salience. Salience can be expressed in many ways including, light and colours. A wide range of technologies can be designed to show such qualities (e.g. Follow-the-light [251]). Therefore, an avenue for future work is to explore the different ways of expressing salience, examine how technologies can be designed to incorporate them and investigate their impact on navigational decision-making

Empirical work This thesis presented a breadth exploration of the implicit cues that can be used to influence decision-making. Chapter 3 explored subliminal cues, Chapter 4 and Chapter 5 examined supraliminal social cues and Chapter 6 and Chapter 7 explored supraliminal physical cues. This wide exploration indicates that there is a need for a deeper exploration within each of the studied cues in order to gain an in-depth understanding. Therefore, future work should carry out more empirical work to gain an in-depth understanding of impact of designed technologies. In addition, The studies presented in Chapter 5 and Chapter 7 use a specific setup of two to three path choices. An avenue for future work, hence, is to explore the impact of the designed technologies in different experimental designs. For instance, how adding more path choices affects the findings.

Evaluation This thesis evaluated the impact of two nudging mechanisms and the cues they present on navigation decisions in controlled settings. The evaluation study in Chapter 5 evaluated the impact of social cues, presented in floor interfaces, on navigation decisions, in the lab. In addition, Chapter 7 evaluated shape-changing walls and how they impact navigation decisions in controlled VR setting. While such controlled settings offered more control of the confounding variables, it affected the ecological validity and limited our understanding of the impact of the social cues in ecologically valid conditions. Future work should extend this work and evaluate the designed technologies in-the-wild. For instance, one direction for a future in-the-wild study is to study the impact social cues, presented as footprints on interactive floor interfaces, on navigation decisions in public spaces. As a first step, the study can examine user behaviour with two path choices. Another future direction for an in-the-wild study is to deploy a physical prototype of a shape-changing wall in a public setting (e.g. museum) and collect users impressions and reactions of it. Furthermore, Future work can develop a physical shape-changing wall of the type Zero-Crossing (examined in Chapter 7) and examine its impact on providing navigational guidance within a public space. In-the-wild evaluations provide a long-term understanding of technologies in their natural setting. However, researchers have no control over intervening variables in such contexts which can make evaluating the impact of a technology on users' behaviours particularly challenging. Other difficulties with in-the-wild evaluations occur when researchers face technological faults, misuse of technology, and when and how to maintain them. Researchers need to prepare, in advance, alternative plans that address such issues.

A Decision-making Process The work presented in this thesis examined a decision-making process. Such process can be extremely challenging to study due to the several variables that play a role in it. Because of this, I used quantitative and qualitative methods to study the impact of the designed technologies on participants behaviours and decisions (Chapter 5 and Chapter 6). However, the impact of these technologies on decision-making may not always be behavioural, it is possible that these technologies may result in cognitive responses. In this case, it would require technologies such as brain-computer interfaces to examine their influence. Future work should address the challenges associated with studying decision-making processes and explore better methods to study them. Future efforts should also explore how technologies can facilitate decision-making processes in various domains.

8.4 Concluding Remarks

In this thesis, I explored how can ambient technologies be utilised to subtly facilitate, guide and influence navigational decision-making while exploring indoor environments. To address this overarching research question, I examined literature from various domains including, environmental psychology, behavioural economics, behaviour change and human-computer interaction. Together, these domains help in uncovering great potentials of ambient technologies and how they can be leveraged to unobtrusively alter spatial behaviours.

The work presented in this thesis is important for facilitating navigation and supporting people while making their navigation decisions in novel environments. In addition, the designed technologies can help in organising and modulating flow of visitors in public spaces, which is essential during situations of crowding or disease pandemics, and hence, achieve a naturally-controlled circulation. The way that these technologies are designed ensures that people's primary task of exploration is not negatively affected.

This thesis lays the foundation for future efforts that aim to incorporate technologies in our everyday environments, particularly those that provide functional goals such as supporting navigation. Furthermore, this work inspires and opens up new research directions for using architectural elements such as floors and walls in guiding and facilitating navigational decision-making.

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APPENDIX

A

APPENDIX A: CHAPTER 3 STUDY MATERIALS

A.1 Stimuli Used in Exploring Subliminal Cues Study

Figure A.1: Image Stimuli used in the study taken from Snodgrass et al. [277]

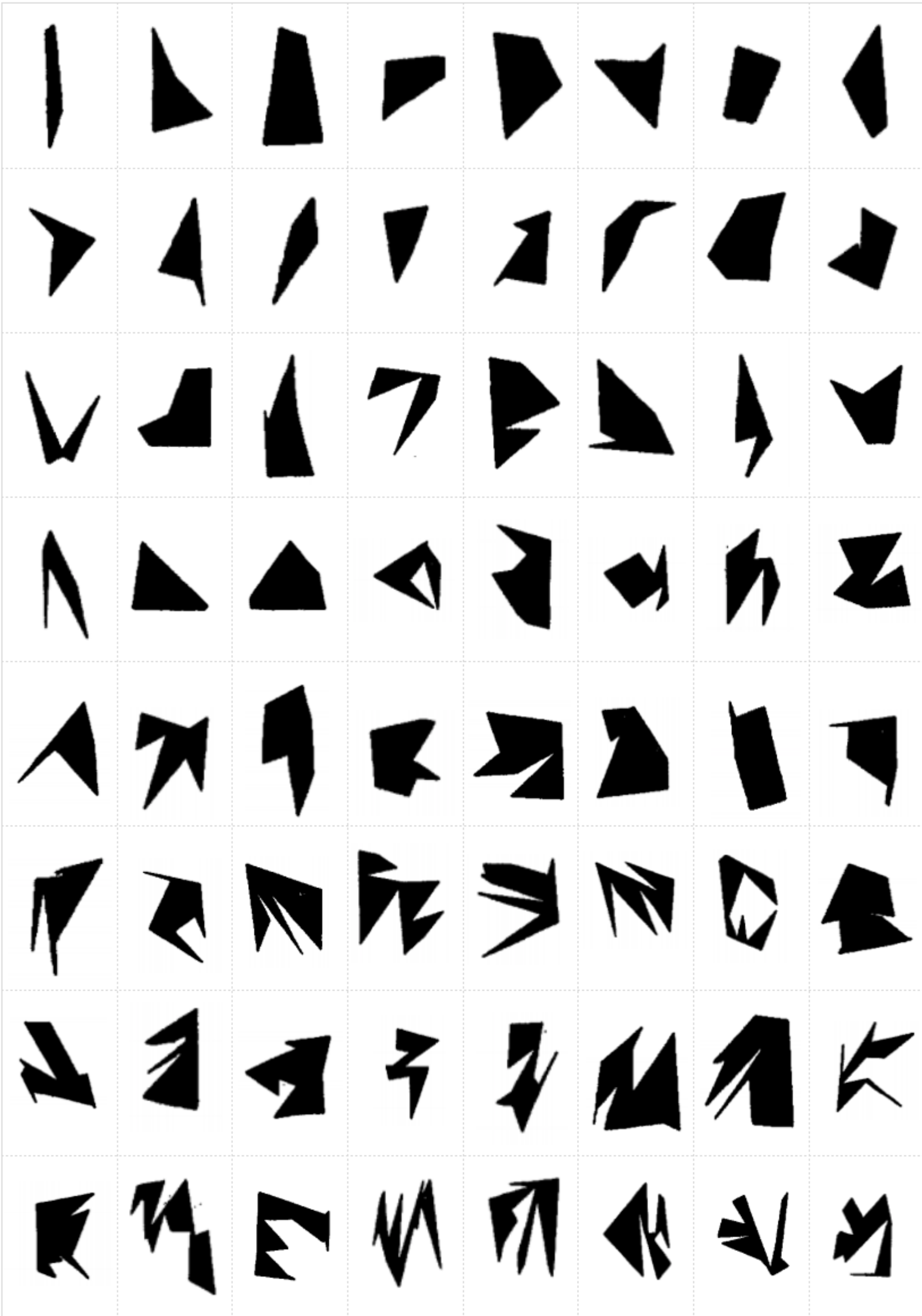


Figure A.2: Geometric shapes stimuli used in the study are irregular four, six, eight, twelve and sixteen-point polygons taken from Vanderplas et al. [311]

aisle	alert	amount	angle	animal	ankle	answer	area
author	avenue	brain	bridge	budget	camera	carpet	child
cloud	coach	east	engine	essay	fence	forest	gold
golf	guest	hight	honour	income	joint	kettle	ladder
liquid	magnet	mail	method	minute	motive	needle	notice
origin	oven	parcel	paste	phase	plot	proof	range
rubber	scent	signal	sleeve	slice	system	trace	truth
tunnel	urban	value	vision	volume	wallet	wisdom	world
yard	youth						

Figure A.3: Word Stimuli are nouns with four to six letters with average familiarity of 545.05. Stimuli were derived from the MRC Psycholinguistic Database [335]

APPENDIX

B

APPENDIX B: CHAPTER 4 STUDY MATERIALS

B.1 A list of Generated Visualisations for "Traces of Navigation Behaviour"

Spots or dots on the floor.

Wading using Augmented Reality.

Flow animations showing density and speed of population.

Little people signs guiding you to popular areas.

Roads connecting people to most popular routes.

Traces in the form of lines.

Grass worn down to show paths people walk in.

Arrows showing paths where size shows speed or number of people.

Accumulation of litter.

Worn-out floor.

Colour changes.

Swarm pattern.

Stream traces.

Using intense smell means more people.

Displaying flowers/greens growing. More people would result in a greener area.

Curvy lines showing density.

Bee behaviour: more people, bees would be flying away, no people would result in bees being together.

Footsteps.

Showing a polished floor when less people are there.

Heatmap.

Audio mapping:Loud audio in case of crowds.

Flow density indicators (Virtual wind tunnels).

B.2 Study 1: Evaluation Study Interview Questions

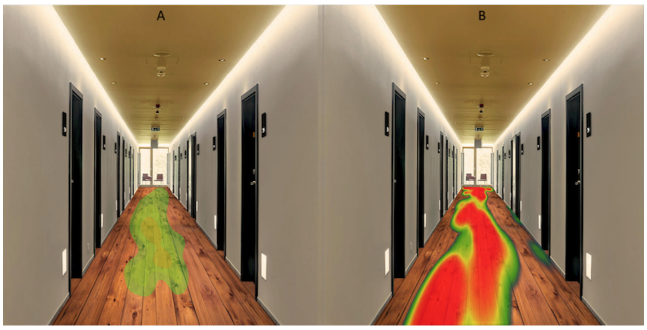
Part 1:

Q1.1: Which path choice would you choose and why?

☐ A ☐ B

Q1.2: Which path choice would you choose and why?

☐ A ☐ B

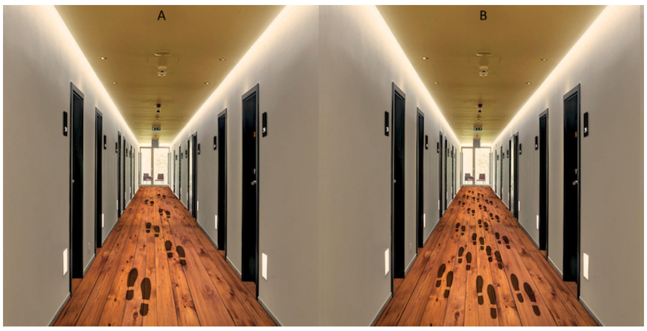


Q1.3: Which path choice would you choose and why?

☐ A ☐ B

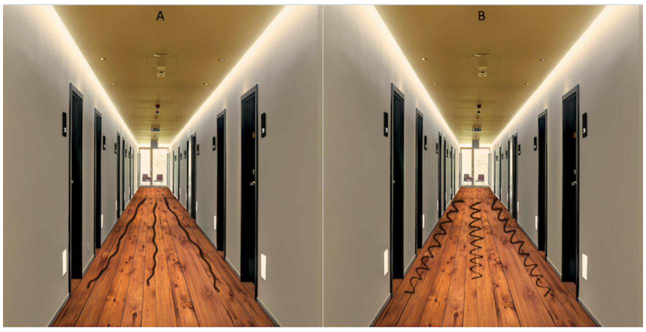
Q1.4: Which path choice would you choose and why?

☐ A ☐ B



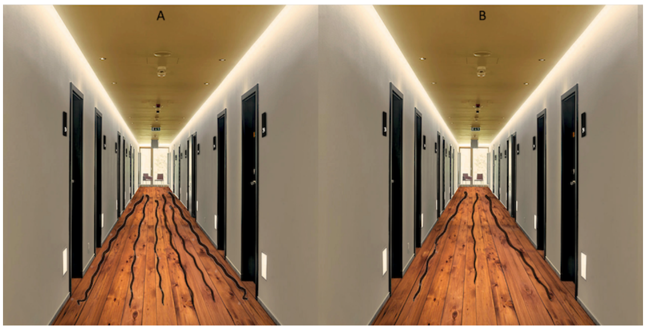
Q1.5: Which path choice would you choose and why?

☐ A ☐ B



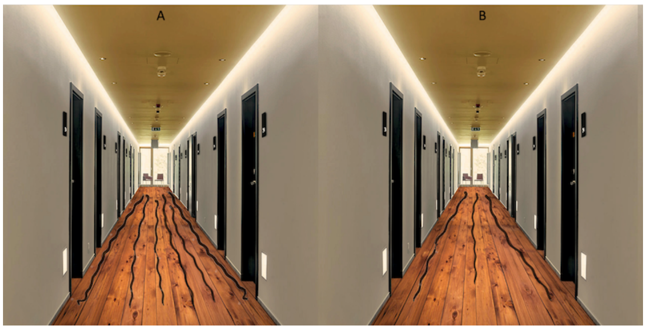
Q1.6: Which path choice would you choose and why?

☐ A ☐ B



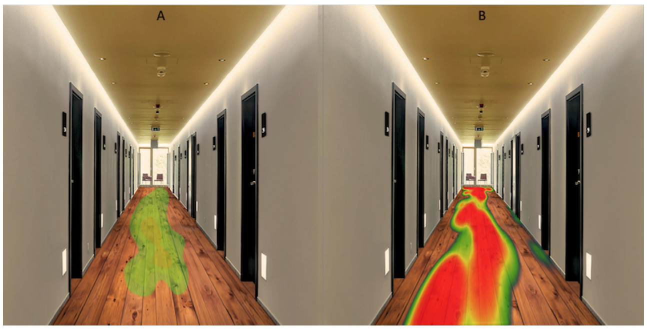
Part 2:

Q2.1: What do you think the following visualisation means?



Answer:

Q2.2: What do you think the following visualisation means?



Answer:

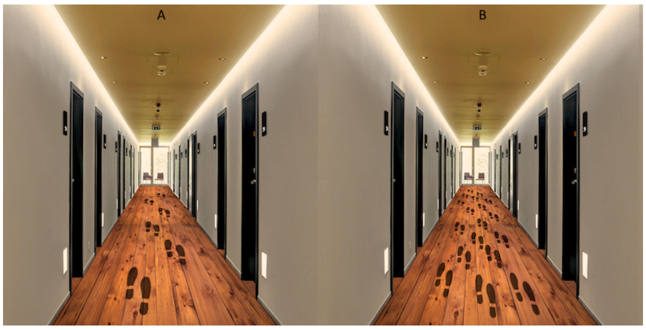
Q2.3: What do you think the following visualisation means?

Answer:

Q2.4: What do you think the following visualisation means?

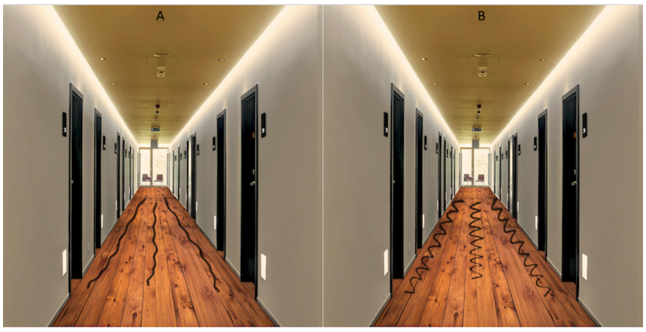
Answer:

Q2.5: What do you think the following visualisation means?



Answer:

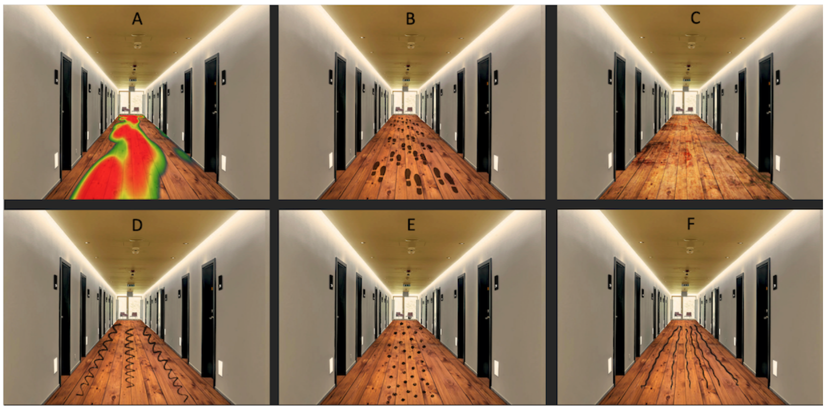
Q2.6: What do you think the following visualisation means?



Answer:

Part 3:

Which of the following visualisations can be used to represent traces of navigation behaviour of other people? Choose the best three. A, B,C, D, E.



1. 2. 3.

Part 4:

What other visualisations can you think of can be used to represent pedestrian density?

Answer:

B.3 Study 2: Design Activity

Warm-up Drawing Activity

Draw how would you imagine the footsteps of three friends while exploring a museum together.

Problem Scenario 1:

Peter is a developer at Bristol museum. He developed a system to guide and direct people by tracking and presenting the traces of the visitors on the floor. Given that people follow others while they explore new spaces, he showed a number of artificial traces on the same interactive floor that lead to the directions he wanted. However, Mike, the planning manager at the museum, was unhappy with the current representation of the traces and he thinks that the representation should be enhanced. Mike is not sure how to improve the current representation and he needs your help to achieve this.

Comparing the current representation with real footsteps, **HOW** would **improve** the visual features of the single footsteps representation to make it more realistic?

HOW would you **change** the current footsteps representation when multiple people are using the system at the same time?

HOW would you **convert** the static footsteps representation to a dynamic representation and **HOW** it can be **used**?
(e.g. vibration→ when they are freshly created)

If more information can be added to the footsteps representation, **WHAT** information would be **useful** to you about people who took that navigation direction?
(e.g. gender)

Problem Scenario 2:

Mike has also discovered that people were not convinced that the artificial traces belonged to past visitors. People thought that the traces were an indication of direction (e.g. footsteps stickers) and not traces of real people.

WHY do you think this problem occurred?

HOW would you **represent** footsteps to help a museum visitor understand that these traces belong to previous visitors?

B.4 List of the Ideas Generated During the Design Activity

	Idea	**Description**
1	Pacing	Adding more diversity in pacing
2	Size	Adding more diversity in size
3	Diverging paths	Creating divergent paths
4	3D imprint	Choose a texture to mimic foot impressions
5	Matching gait	Matching the gait of the person
6	Representation for disabled people	Using a different representation for people with disabilities
7	Sharp footprints	using a sharper footprints representation than the one used in the study
8	Soft colours	Using soft colours in the footprints
9	Less footprints	Not showing too many footprints on the floor
10	Arrows	Foot shape would be more defined when arrows are added to it
11	Simple	Having less detail, more simple, does not have to look like real footprints
12	No change	Current footprint representation require no change
13	Use different footprints for each theme	Using different footprints leading to different exhibits/themes
14	Generic	Using more generic footprints representation
15	Barefoot	Using barefoot representation instead of shoes prints
16	Shoes types	Presenting the different types of shoes (e.g. small, heels)
17	Smaller size	Using a smaller footprint size compared to the one used in the study
18	Larger stride	Using a larger stride compared to the representation used in the study
19	Scattered footprints	Making footprints more scattered
20	Enhanced contours of shape	Enhancing or highlighting the contour of the footsteps
21	Flower blooming animation	Adding a flower blooming animation to the footsteps
22	Shadows	Adding shadows to the current footprints

23	Different walking behaviours	using different walking behaviours to present different people in a space
24	Different weights	using different weights to present different people in a space
25	Different Sizes	using different footsteps sizes to present different people in a space
26	Large feet	Combining information to create a super long feet
27	Different pattern	Using a different pattern for each person
28	Different colour	Using a user specific colour
29	Average path	Rather than presenting each person, present the average path
30	Type of shoes	Present the different types of shoes of people
31	User-defined symbols	Using user-defined shapes/ symbols (e.g. flowers)
32	Half of the footprint	Presenting half of the footprints to reduce clutter
33	Big Blob	A bog blob to represent all people of the same colour
34	Single beam	Using a single beam instead of using individual footprints
35	Halos	Using halos of people instead of individual footprints
36	Thickness of line	Using thickness of traces rather than individual footprints
37	Illuminated traces	Making popular traces brighter and more illuminated
38	Abstract lines	Using thickness of lines to represent people
39	Dynamic Size	visualisations become larger for a short time after creation or after standing for a long time on a specific place
40	Dynamic colour	Colour changes is response to certain events
41	Dynamic shape	Shape of the footprint changes in response to certain events
42	Machine Learning	Using machine learning to study user behaviour and suggest paths to take
43	Sound	Footsteps sound plays when someone steps on the floor
44	Light changes	Controlling lighting of room based number of people
45	Footsteps walking animation	Creating animations of footsteps walking periodically

46	Pulsating footsteps	Footsteps pulsates for a short period of time when they are created
47	Glowing or Fainting	Recent footsteps glow whereas old ones become faint
48	Sand feeling	Provide the feel of stepping on sand
49	Ripple effect	Creating a ripple effect when it is created
50	Bright Colours based on time	The colour of the footsteps becomes brighter when a person steps on it for a long time
51	Reaction when stepping on someone's footsteps	Create a reaction when someone steps of other people's footprints
52	Vibration	Creating a vibration with every step
53	Size shrinking	footsteps shrink over time
54	Vanishing footsteps	footsteps vanish after a period of time
45	real-time creation	Users can see the creation of the their footsteps
56	moving footsteps	Footsteps of previous visitors can be seen moving
57	Removing footsteps of others when stepping on it	Footsteps of previous visitors are removed when a person steps on it
58	Wind sensation	Adding a wind sensation from the floor when someone steps on the floor
59	Age	Adding age to footsteps representation to make it more useful while navigation
60	Speed	Adding speed of people to footsteps to make it easier while navigation
61	Relevant Education	Adding education to footsteps representation to make it more useful while navigation
62	Language Fluency	Adding fluency information to footsteps representation to make it more useful while navigation
63	Time	Adding the time of the day to the footsteps representation
64	Time since creation	Adding the time since the footsteps were created to the footsteps representation

65	Group Size	Adding to the footsteps representation whether they visited as a couple, family, solo or as a group
66	Busy location	Adding information about how busy the location is within footsteps, for instance by changing their colour
67	Time spent	Adding time spent in a specific place to the footsteps
68	Purpose	Including the reason for visiting (e.g. pleasure, work) to the footprints
69	Familiarity	Adding the familiarity of the space to the footsteps to identify regular visitors and first-timers
70	Gender	Adding gender to the footsteps
71	Specialisation	Adding specialisation or field of study to the footprints
72	Destination	Adding the destination people are heading to in the footprints
73	Interests	Adding interests (Science, Literature, Art) to the footprints
74	Distance to destination	Adding how far the destination is from their current location
75	Time to reach destination	Adding time to reach the destination to the footprints
77	Wheelchairs representation	Using a specific representation for people who use wheelchairs
78	additional information	Adding additional information related to the place/event. For instance, Expert, Paper presenter or Professor
79	Nationality	Adding nationality to the footsteps
80	Favourite place	Adding favourite places to the footsteps

APPENDIX C

Appendix C: Chapter 5 Study Materials

C.1 Scenarios used during exploration and search

Scenario 1: Explore

The researcher (while the participant is standing at the starting point): *"You are attending a conference. The posters session has started and you have enough time to explore and have an overview about the current research in HCI"*

The researcher: Go a head and have a look while I setup few things, come back here once you are done.

`Once the participant finishes the explore and returns to the starting point, the researcher asks her to wait and sit on a chair outside the study area.`

`In the meantime, the researcher reveals the posters codes.`

Scenario 2: Search

`The participant is given a piece of paper and pen to write down the required information.`

The researcher: Each poster has a poster code which is located at the bottom of the poster (image shown).
The researcher: *"You are in a hurry you have 1 min before the start of the next paper session, and you need to find and write down the first author of a poster with the code: BAECD."*
The researcher: Come back to this point once you are finished.

C.2 Interview Questions

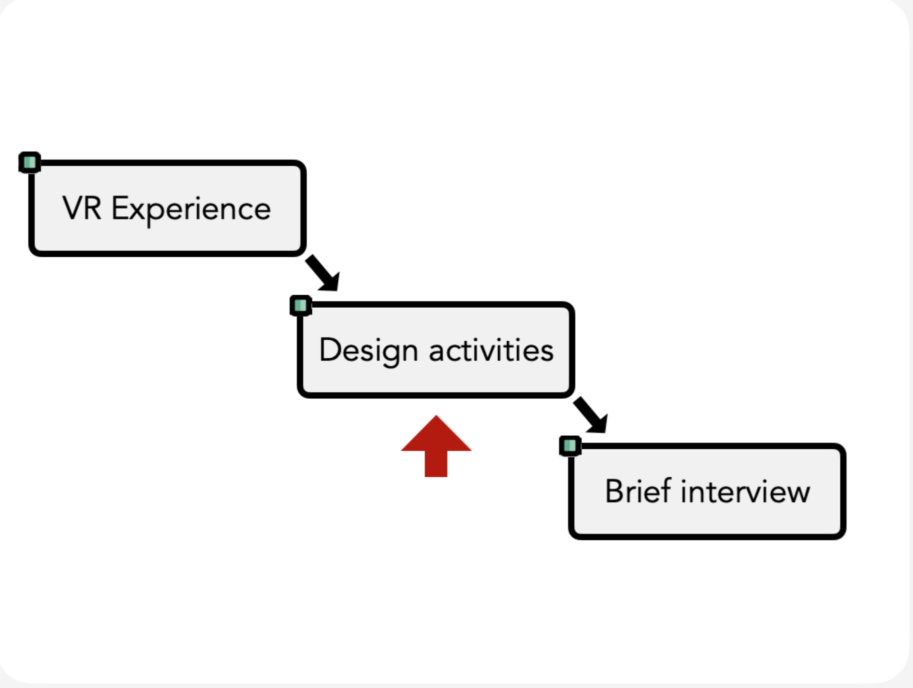
- Why did you choose right/left in the first task (explore)?
- Why did you choose right/left in the second task (search)?
- Have you noticed what was shown on the floor? If yes, explain what was it?
- Have you noticed your own footprints? If yes, do think this have affected your behaviour during the tasks?
- What do you understand from these footprints and what do think they mean?

APPENDIX D

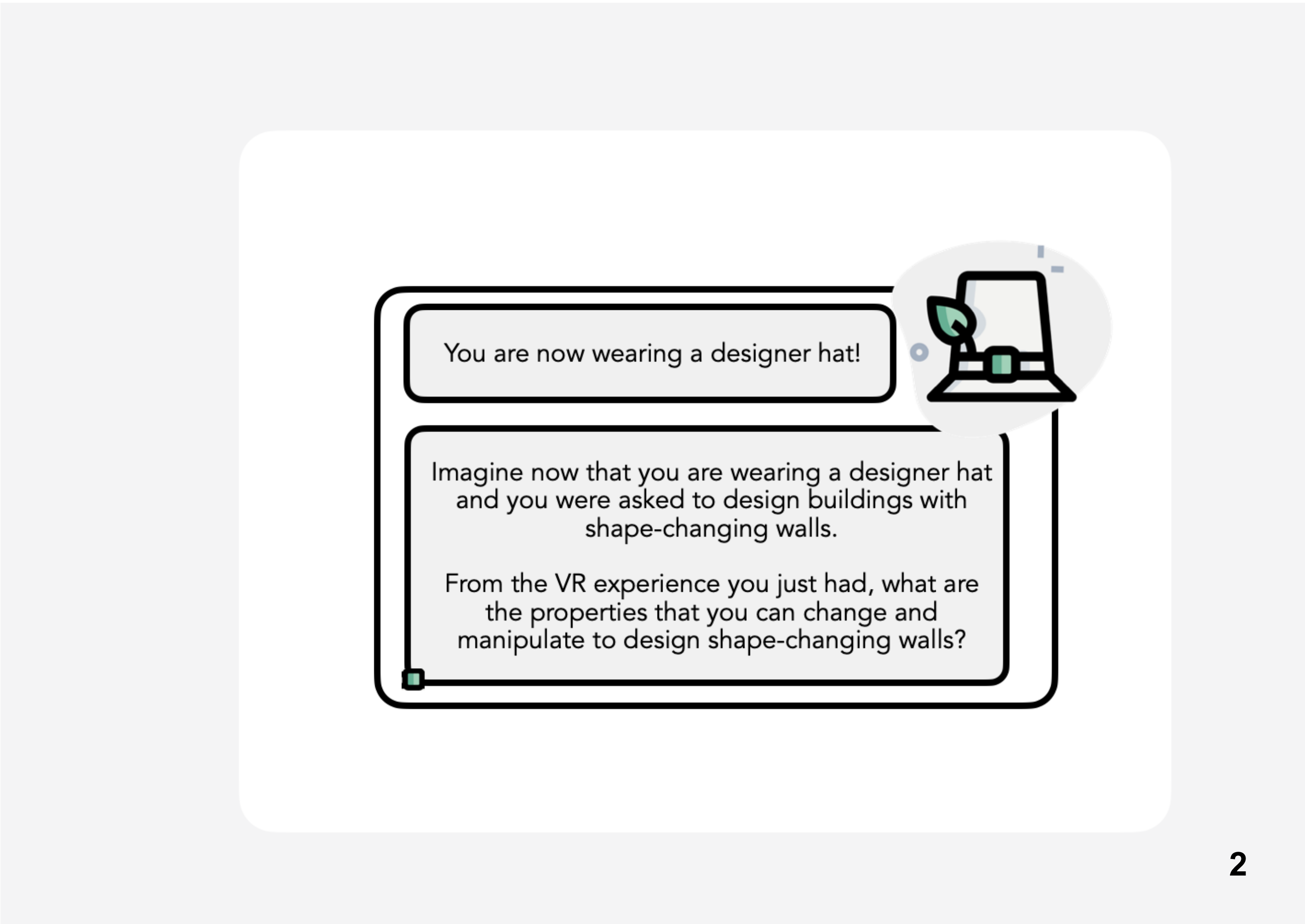
APPENDIX D: CHAPTER 6 STUDY MATERIALS

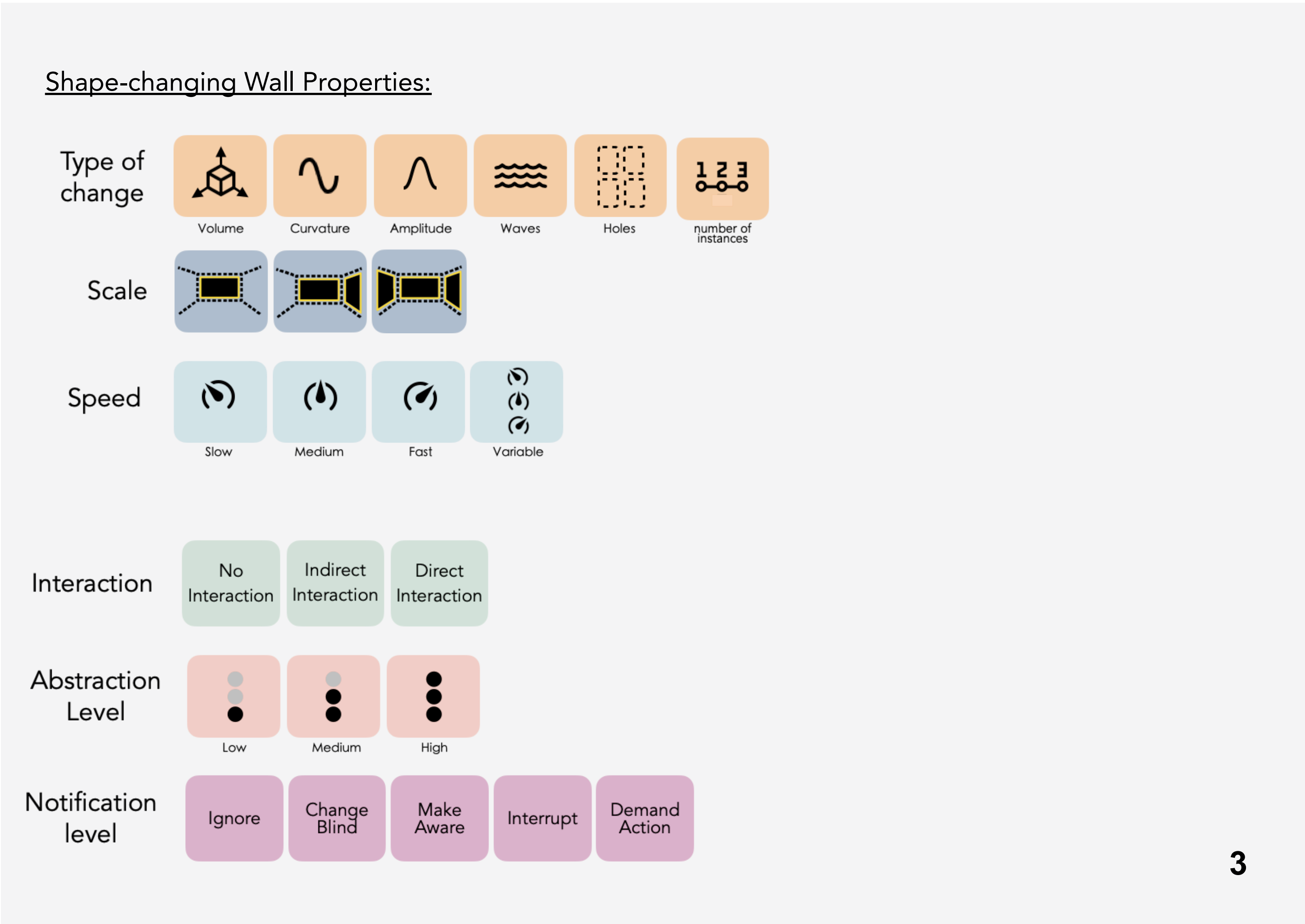
D.1 Online Design Activities

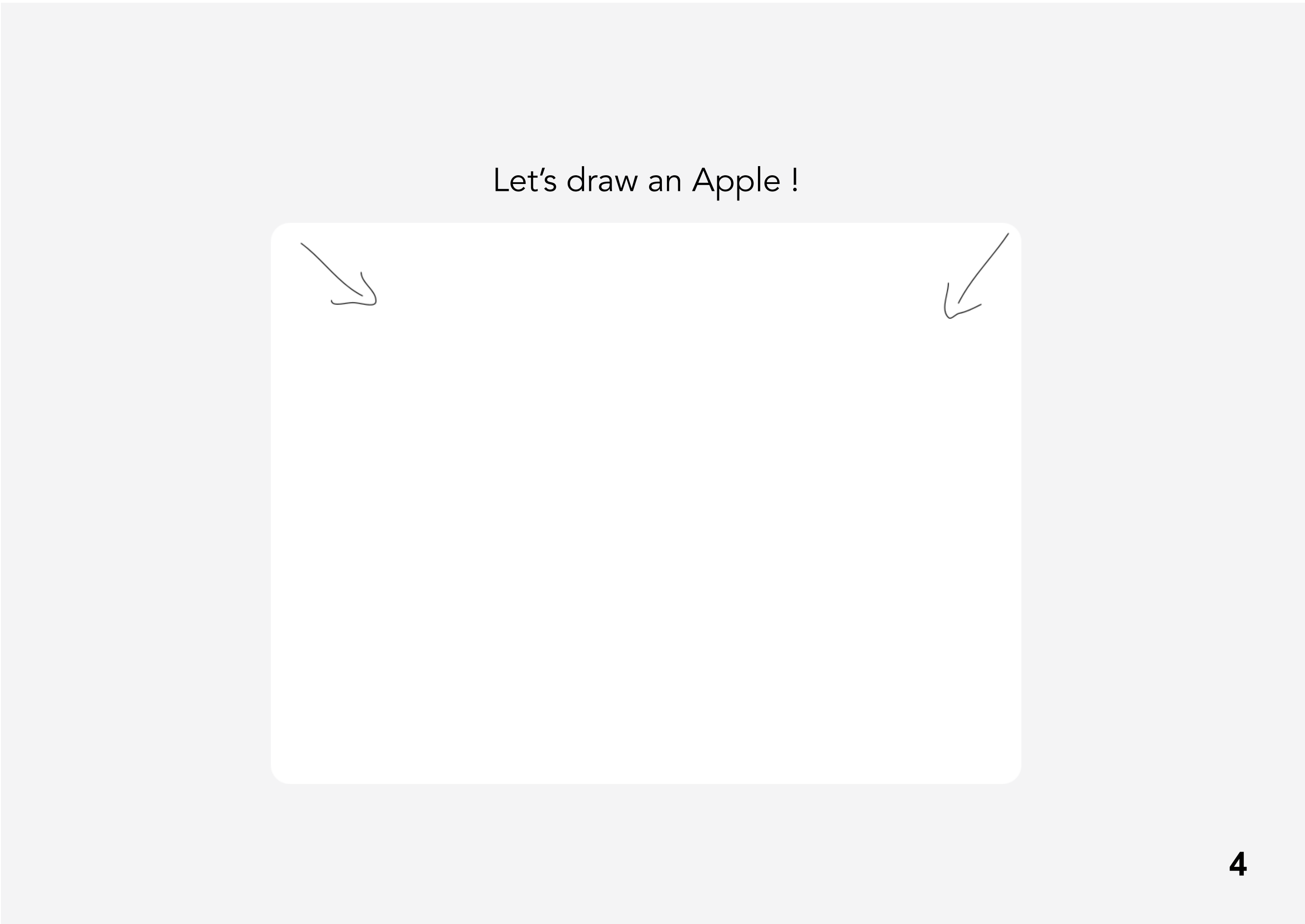
Participant No.: Pxx



1

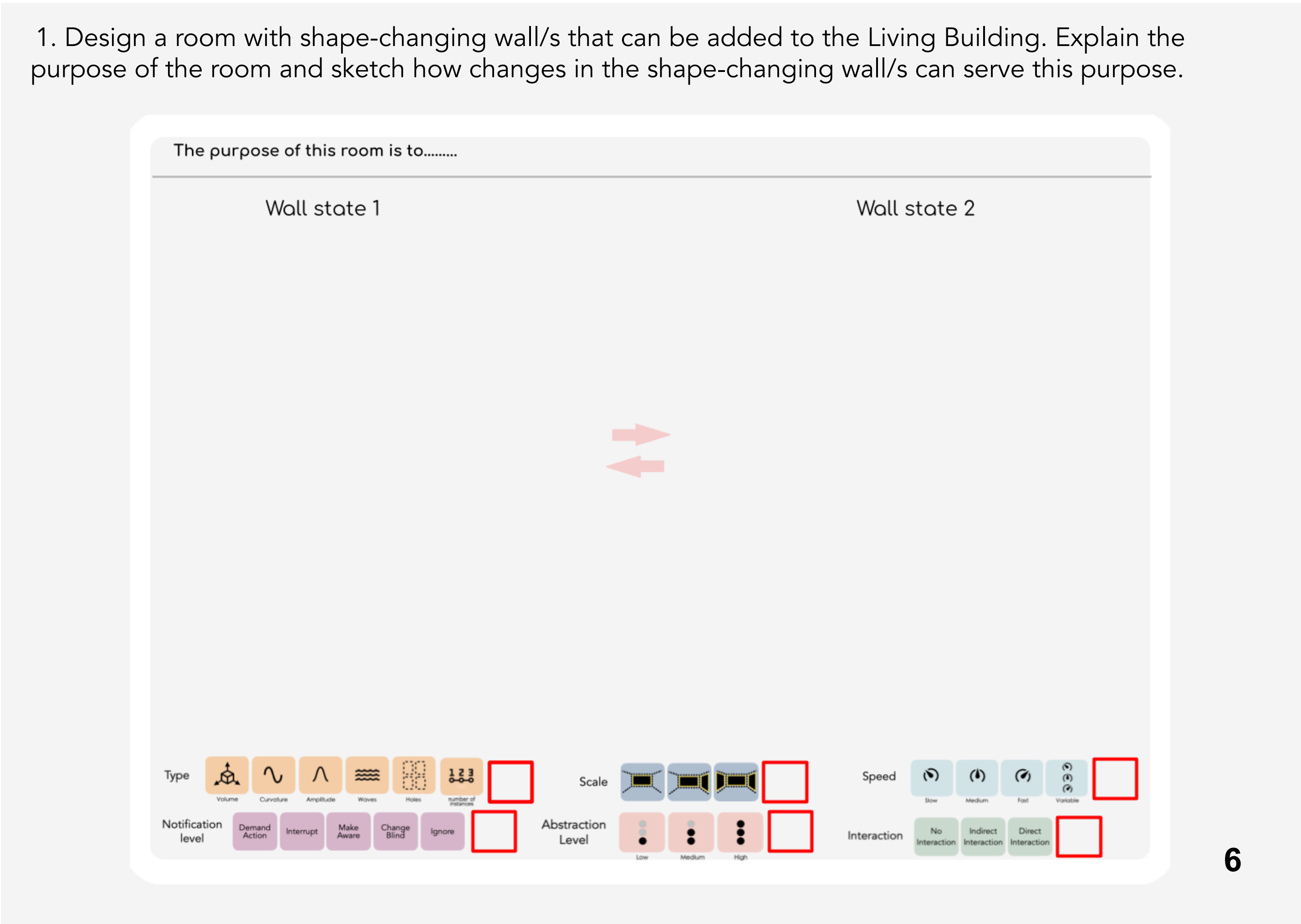

You are now wearing a designer hat!
Imagine now that you are wearing a designer hat and you were asked to design buildings with shape-changing walls.
From the VR experience you just had, what are the properties that you can change and manipulate to design shape-changing walls?
2


Shape-changing Wall Properties:
Type of change
Volume
Curvature
Amplitude
Waves
Holes
number of instances
Scale
Speed
Slow
Medium
Fast
Variable
Interaction
No Interaction
Indirect Interaction
Direct Interaction
Abstraction Level
Low
Medium
High
Notification level
Ignore
Change Blind
Make Aware
Interrupt
Demand Action
3


Let's draw an Apple !
4

Design Activity 1

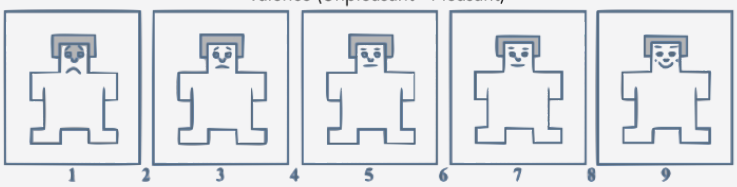
5


1. Design a room with shape-changing wall/s that can be added to the Living Building. Explain the purpose of the room and sketch how changes in the shape-changing wall/s can serve this purpose.
The purpose of this room is to.........
Wall state 1
Wall state 2
Type
Volume
Curvature
Amplitude
Waves
Holes
number of instances
Scale
Speed
Slow
Medium
Fast
Variable
Notification level
Demand Action
Interrupt
Make Aware
Change Blind
Ignore
Abstraction Level
Low
Medium
High
Interaction
No Interaction
Indirect Interaction
Direct Interaction
6

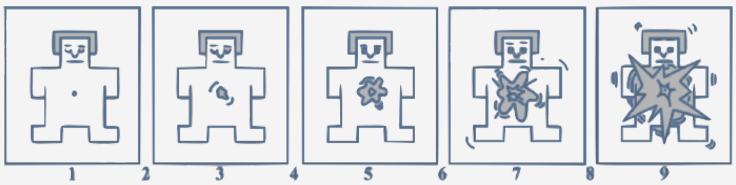
2. How would you describe the emotional state of your wall design, if any? Why?

Valence (the pleasantness of the wall design), **arousal** (the intensity of emotion provoked by the wall design), and **dominance** (the degree of control employed by the wall).

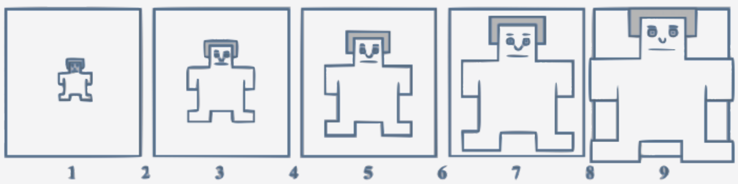
Valence (Unpleasant - Pleasant)



Arousal (Calm - Exciting)



Dominance (Controlled - Controlling)



7

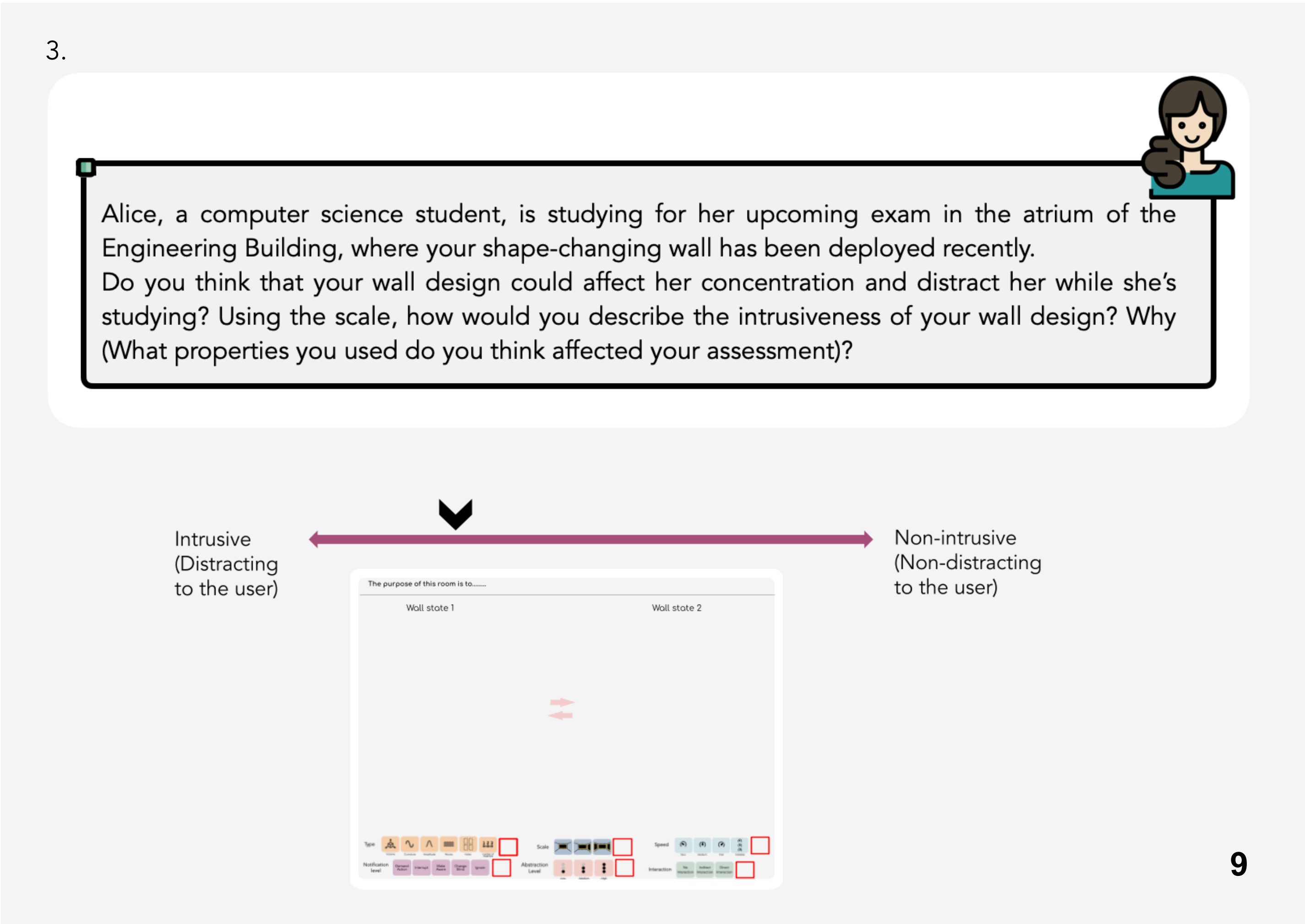
We will use the term

Intrusiveness to describe the degree to which your design demands attention from users.

Intrusive designs require a large amount of attention, which can distract the user from their on-going tasks.

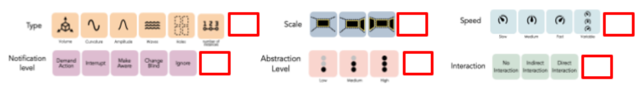
Non-intrusive designs **do not** demand too much attention from the user and are hence not distracting to the user.

8


3.
Alice, a computer science student, is studying for her upcoming exam in the atrium of the Engineering Building, where your shape-changing wall has been deployed recently.
Do you think that your wall design could affect her concentration and distract her while she's studying? Using the scale, how would you describe the intrusiveness of your wall design? Why (What properties you used do you think affected your assessment)?
Intrusive (Distracting to the user)
Non-intrusive (Non-distracting to the user)
The purpose of this room is to......
Wall state 1
Wall state 2
9

4. How would you design the room on the other extreme? What properties would you change to make it intrusive/non-intrusive?

<Copy the design made in Q1 and place it based on the assessment in the previous question, so that the participant can compare and design the other extreme.>



Intrusive
(Distracting to the user)

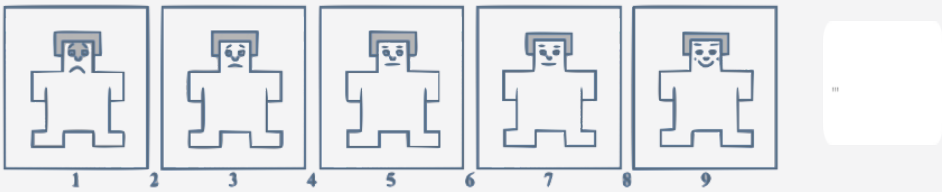
Non-intrusive
(Non-distracting to the user)

10

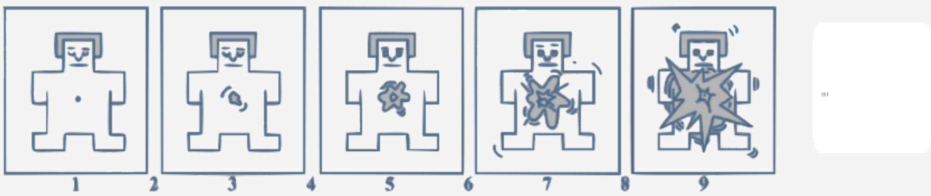
5. How would you describe the emotional state of your wall design, if any? Why?

Valence (the pleasantness of the wall design), **arousal** (the intensity of emotion provoked by the wall design), and **dominance** (the degree of control employed by the wall).

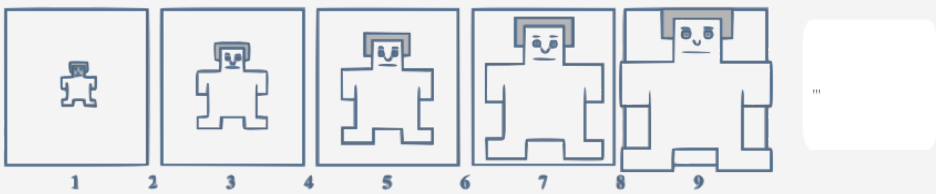
Valence (Unpleasant - Pleasant)



Arousal (Calm - Exciting)



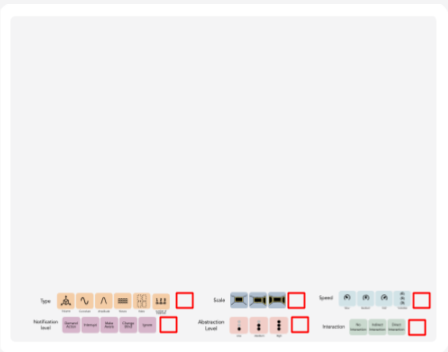
Dominance (Controlled - Controlling)



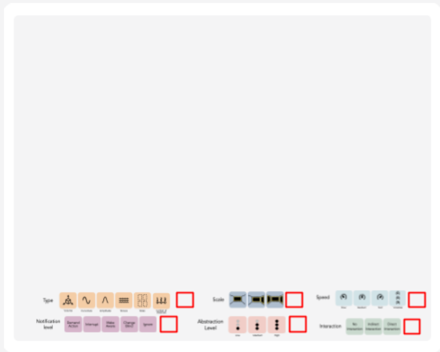
11

<CQ>

4. How would you design the room on the extremes? What properties would you change to make it intrusive/non-intrusive?



<Copy the design made in Q1 and place it based on the assessment in the previous question, so that the participant can compare and design the other extreme.>



Intrusive
(Distracting to the user)

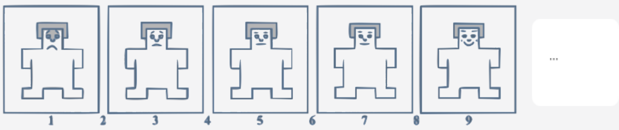
Non-intrusive
(Non-distracting to the user)

12

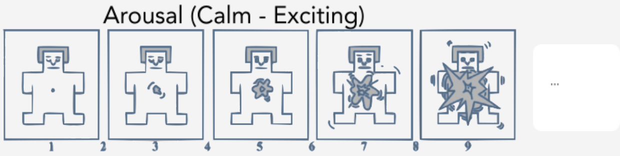
5. How would you describe the emotional state of each design, if any? Why?

Valence (the pleasantness of the wall design), **arousal** (the intensity of emotion provoked by the wall design), and **dominance** (the degree of control employed by the wall).

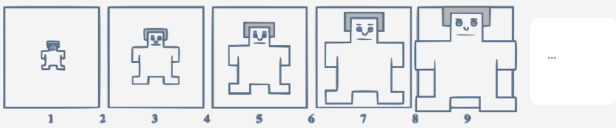
Valence (Unpleasant - Pleasant)



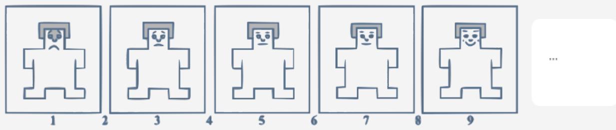
Arousal (Calm - Exciting)



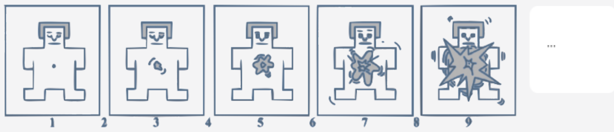
Dominance (Controlled - Controlling)



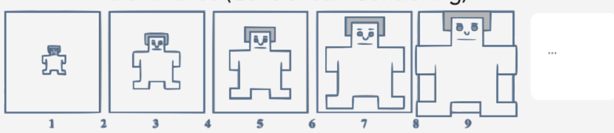
Valence (Unpleasant - Pleasant)



Arousal (Calm - Exciting)

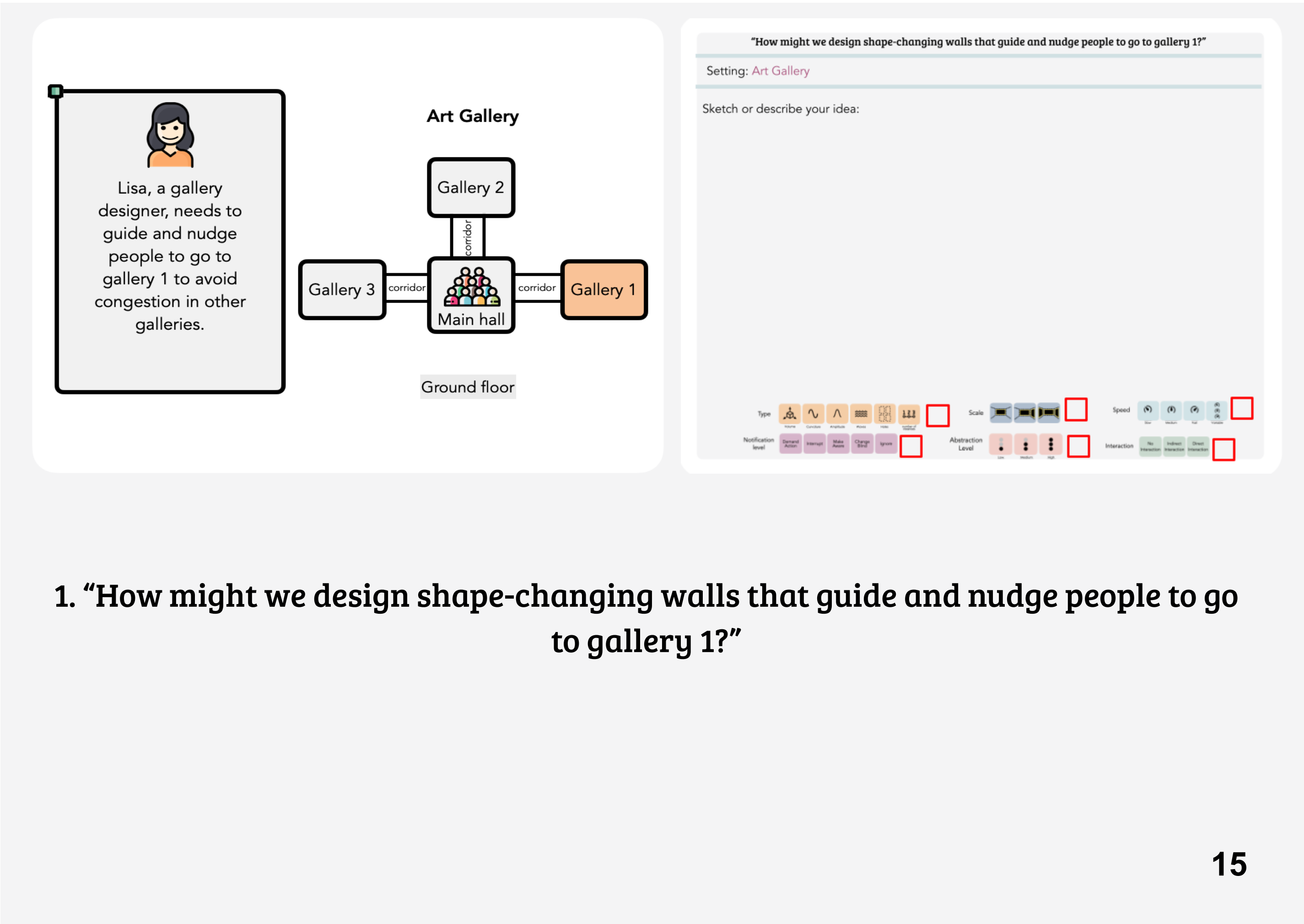


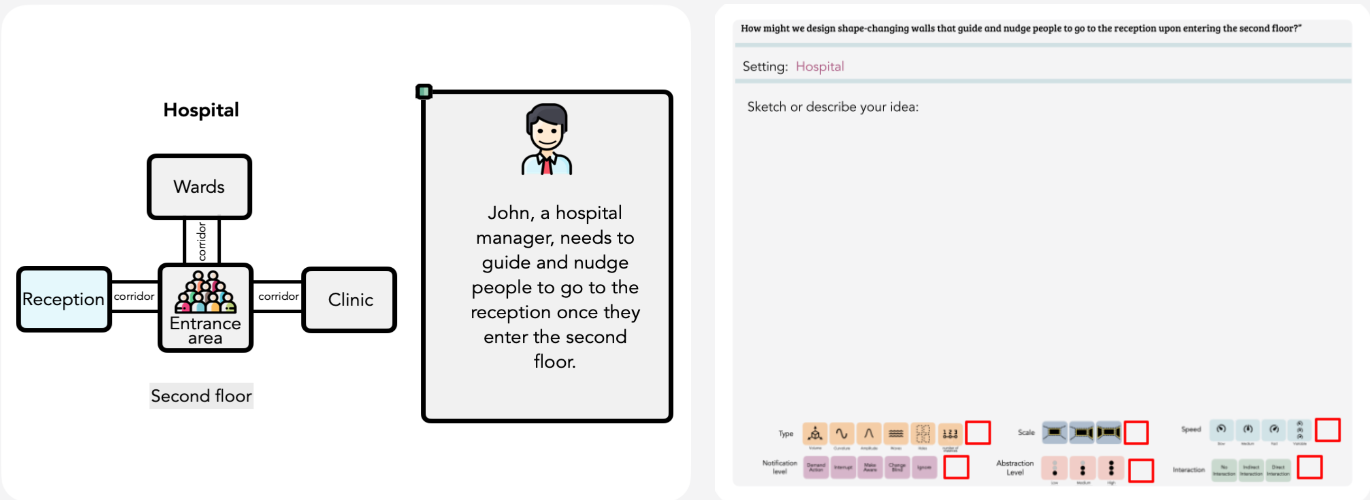
Dominance (Controlled - Controlling)



13


Design activity 2
14


Lisa, a gallery designer, needs to guide and nudge people to go to gallery 1 to avoid congestion in other galleries.
Art Gallery
Gallery 2
corridor
Gallery 3
corridor
Main hall
corridor
Gallery 1
Ground floor
"How might we design shape-changing walls that guide and nudge people to go to gallery 1?"
Setting: Art Gallery
Sketch or describe your idea:
1. "How might we design shape-changing walls that guide and nudge people to go to gallery 1?"
15



2. “How might we design shape-changing walls that guide and nudge people to go to the reception upon entering the second floor?”

16

What is the difference between designing shape-changing walls for an art gallery and for a hospital?

17

3. How would shape-changing walls be used to serve a functional purpose in the following contexts?

Public Space

School

Work

18

The End !

19

APPENDIX E

APPENDIX E: CHAPTER 7 STUDY MATERIALS

E.1 Scenario and Questions for A, B, C and D Buttons

`After giving an overview of the study, the researcher asks the participant to wear the VR viewer and select on of the four available buttons: A, B, C or D.`

Researcher: Select the...(A, B, C or D)...button.

Researcher: Without moving from your current location, take a 360° look around you and then describe what you see? `(The researcher takes a note of the location of the shape-changing wall)`

Researcher: *"Imagine now that You are in an art gallery, which route would you choose to explore the gallery? why?"*

(Conditional question if the participant did not make any reference to the shape-changing walls) Researcher: Have you noticed the shape-changing walls? How does the shape-changing walls make you feel? How do you feel when you move closer to them?

Researcher: Now walk in the route you selected until you reach the door at the end of the route. Please mention anything that comes to your mind while you walk.

(After 3 seconds) Researcher: You will be directed to the main menu after you reach the door and I'll tell you then which button to select next.

The above scenario and questions are repeated four times, in each of the studied shape-changing walls types.

E.2 Scenario and Questions for Compare Types Button

Researcher: Now click on the *Compare Types* button.

Researcher: Have a 360° look around you, without moving from your current location and describe what you see. (Corridor 1: Zero-Crossing with wave-like shape, Corridor 2: Amplitude with Cubes, Corridor 3: Concave Curvature, Corridor 4: Convex Curvature)

Researcher: *"Imagine now that you are managing this art gallery: which wall type would you choose to install in the gallery in order to nudge people to follow certain routes? Why?"*

Researcher: What about the other types? Why do you think you would not choose them?

Researcher: Now walk in the route you selected until you reach the door at the end of the route.