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Examining the Sense of Agency in Human-Computer Interaction

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Declaration

I hereby declare that this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

Signature:

Summary

Humans are agents, we feel that we control the course of events on our everyday life. This refers to the Sense of Agency (SoA). This experience is not only crucial in our daily life, but also in our interaction with technology. When we manipulate a user interface (e.g., computer, smartphone, etc.), we expect that the system responds to our input commands with feedback, as we desire to feel that we are in charge of the interaction. If this interplay elicits a SoA, then the user will perceive an instinctive feeling of "I am controlling this". Although research in Human-Computer Interaction (HCI) pursuits the design of intuitive and responsive systems, most of the current studies have been focussed mainly on interaction techniques (e.g., software-hardware) and User Experience (UX) (e.g., comfort, usability, etc.), and very little has been investigated in terms of the SoA i.e., the conscious experience of being in control regarding the interaction.

In this thesis, we present an experimental exploration of the role of the SoA in interaction paradigms typical of HCI. After two chapters of introduction and related work, we describe a series of studies that explore agency implication in interaction with systems through human senses such as vision, audio, touch and smell. Chapter 3 explores the SoA in mid-air haptic interaction through touchless actions. Then, Chapter 4 examines agency modulation through smell and its application for olfactory interfaces. Chapter 5 describes two novel timing techniques based on auditory and haptic cues that provide alternative timing methods to the traditional Libet clock. Finally, we conclude with a discussion chapter that highlights the importance of our SoA during interactions with technology as well as the implications of the results found, in the design of user interfaces.

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List of Abbreviations

Abbreviation	Meaning
SoA	Sense of Agency
HCI	Human-Computer Interaction
IB	Intentional Binding
UX	User Experience
VR	Virtual Reality
AR	Augmented Reality
FoA	Feeling of Agency
JoA	Judgement of Agency
RP	Readiness Potential
W	Will
TMS	Transcranial Magnetic Stimulation
SA	Somatosensory Attenuation
ASD	Autism Spectrum Disorder
EMG	Electromyography
SAM	Self-Assessment Manikin
HMD	Head-Mounted Display
1PP	First Person Perspective
IVR	Immersive Virtual Reality
SEM	Standard Error of Mean
PCA	Principal Component Analysis
PAD	Pleasure, Arousal, Dominance
ID	Index of Difficulty
AI	Artificial Intelligence
AHS	Alien Hand Syndrome
MLE	Maximum-Likelihood Estimation

Chapter 1
Introduction

1.1 Motivation

"The interdisciplinary design science of human-computer interaction began by combining the data-gathering methods and intellectual framework of experimental psychology with the powerful and widely used tools developed from computer science."
(Shneiderman & Plaisant, 2005)

Research on human-computer interaction (HCI) is rapidly developing and bringing novel metaphors that intuitively communicate humans with systems. According to Ben Schneiderman, "HCI's paradigm birth came from the happy union of computing technologies with psychological research methods" (Shneiderman, 1980). This refers to theories that account for human behaviour in the design of user interfaces. Indeed, a large number of studies in HCI are dedicated to investigating user experience (UX). The latter refers to the user's attitudes about using a system, which are considered for designing high quality user experiences (Hartson & Pyla, 2012). Different elements that shape UX can be evaluated through empirical methods related to performance measures (e.g., error or speed) and user satisfaction scales (e.g., comfort or enjoyability) to determine the usability of a system (Bevan, 1995, 2001).

However, although HCI research aims to design intuitive systems that give users an experience of being in control (Shneiderman, 2004), the role of the sense of agency (SoA) in designing user interfaces has been little studied. The SoA refers to the experience of being the initiator of one's own voluntary actions, through which we influence the world around us (Haggard, 2017).

This experience is particularly important in our agentive interactions with technology. For instance, when we manipulate a user interface (e.g., on a computer or smartphone), we expect the system to respond to our input commands as we want to feel we are in charge of the interaction. If this action-outcome interplay elicits a SoA, then the user will perceive an instinctive feeling of “I am controlling this”. In contrast, if a system does not support a SoA, then the user might feel discouraged from using it (Limerick et al., 2015) and lose self-attribution of his/her actions’ outcomes.

Despite the increasing emergence of novel interaction paradigms (e.g., touchless systems and automation aids) that are being used in many critical situations (e.g., driving and surgery), current UX frameworks do not include the experience of agency as an element composing user interface design. Yet, many of these interaction scenarios require a high level of agency and responsibility. For instance, in autonomous driving or autopilot mode in aviation (where the system takes some decisions to assist the operator), it is important to provide users with the appropriate feeling of being in control so that they feel responsible for their own actions and the consequences of these (Berberian, 2019). Studying agency in this aspect can support the design of appropriate automation levels that do not disrupt users’ SoA (Coyle et al., 2012).

In another example, touchless interaction is being employed in surgery applications (O'Hara et al., 2014), where surgeons can control imaging systems by gestural actions (not involving any physical contact at all). However, as it is an uncommon input modality (beyond typical keyboards and touchscreens), it is unclear if touchless interaction produces a SoA in users. In these critical situations (e.g., surgery, driving), if users do not experience agency and responsibility, they could diminish their self-attribution of an unfavourable outcome.

While the SoA itself has been little studied in interaction with technology, HCI researchers do acknowledge the importance of designing systems that provide a feeling of being in charge of the interaction. For instance, Ben Schneiderman establishes in his eight golden rules of interface design that user interfaces should “support an internal locus of control” (Shneiderman, 2005). An *internal* locus of control refers to the belief that outcomes result from one’s own actions, while an *external* locus of control refers to the belief that outcomes are not a product of one's personal efforts (Lefcourt, 1991).

In this line, subjective scales to assess users' degree of control have been employed (O'Brien et al., 2018). However, as the term "control" can be quite subjective, recent studies have measured SoA as a means of exploring users' feeling of controlling a system. Measuring agency can give greater insights into how the experience of control is given by users' perception that sensory outcomes from the system are produced by their own actions (Coyle et al., 2012; Limerick et al., 2015; Bergstrom-Lehtovirta et al., 2018). This is because the SoA is a well-studied phenomenon in the field of psychology and cognitive neuroscience and can be assessed using implicit methods (Haggard et al., 2002). Indeed, Limerick et al. suggest that "an interdisciplinary combination of HCI research and cognitive neuroscience to investigate the sense of agency can provide a rich and promising new research area that has the potential to inform both fields in novel ways" (Limerick et al., 2015).

Measuring the SoA can provide relevant insights about the reliability of emerging interaction paradigms. For instance, research on multisensory experiences in HCI is pursuing the integration of all our senses in user interfaces (Obrist et al., 2017). Such integration means that the user not only interacts with systems via visual, auditory or tactile cues, but also through olfactory information (Obrist et al., 2014), for example, in receiving olfactory notifications (Maggioni et al., 2018). The sense of smell is quite powerful in evoking emotions, suggesting a strong potential to improve user experiences by adding realism and immersion, for example, in virtual reality (VR). Therefore, exploring olfactory interfaces through agency measures could be useful to validate their applicability for HCI.

However, since agency measures have emerged from the field of cognitive neuroscience, they can be limited to simple and controlled experiments that might not be suitable for interactive and visual environments typical in HCI (e.g., in VR). For instance, the intentional binding (IB) paradigm provides an implicit measure of the SoA, linking agency experience and perception of time (Haggard et al., 2002). This paradigm can require high visual attention to timing cues that subjects employ to report the time at which events occur (e.g., a small on-screen clock). Therefore, when used in situations involving relevant visual information (e.g., VR and on-screen tasks) this measure might not be suitable. However, by increasing the research on agency within HCI, we might be able not only to use existing paradigms to evaluate SoA but also adapt or develop novel measures of agency that can be more suitable for interactive tasks in our field.

In this thesis, we want to highlight the importance of including agency measures within UX in HCI research. We believe that studying the SoA is crucial to better understand how people interact with technology, in the context of not only causality (e.g., the relationship between actions and outcomes) but also responsibility. This thesis therefore aims to examine how measuring the SoA using implicit measures such as the IB paradigm can give broader insights into user feeling of control in HCI. Improving the user's SoA can potentially result in more engaging commercial devices and software. In order to achieve this goal, we explore the role of the SoA in novel HCI paradigms involving the human senses (including mid-air haptic and olfactory interfaces) as well as measures of agency that could be more suitable for interactive tasks. The overarching research aim is achieved through the following research questions, which are distributed among three main chapters of this thesis (see Table 1.1).

1.2 Objectives and Research Questions

RQ1: Is a SoA experienced in touchless interaction?

The first research question explores whether a typical action performed in touchless systems (a click gesture) produces users' SoA. It is not clear if touch interaction where the user presses buttons and touches screens is perceived as clearer compared with mid-air gestures. Therefore, this research question explores whether a feeling of control is perceived when performing a voluntary action that does not involve physical contact or limit or tactile feedback in comparison with a physical button press.

RQ2: What type of feedback produces greater SoA in mid-air interfaces?

The second research question is dedicated to comparing different types of feedback commonly employed in mid-air interfaces (visual, auditory and mid-air haptic feedback) in order to determine what type of action's outcome produces a greater SoA.

RQ3: Do emotions produced by odours modulate the SoA?

The third research question aims at exploring how emotions produced by exposure to different scents (pleasant, unpleasant and neutral) modulate the SoA. Following literature suggesting that the SoA is influenced by emotions induced by vision, audio and touch, this research question aims to contribute to the literature of SoA by including the sense of smell for agency modulation.

RQ4: Does a positive odour increase the SoA?

Based on prior studies suggesting that a positive emotion (produced via visual, auditory and tactile information) enhances the SoA, the fourth research question investigates whether a positive odour produces a higher SoA compared with a negative odour.

RQ5: Can the IB paradigm be measured using a non-visual timing stimulus?

The fifth research question examines different non-visual timing stimuli to measure IB. Since typical timing methods are based on visual information, this research question explores whether an IB effect is observed when using auditory and tactile stimuli in comparison with traditional visual stimuli.

RQ6: Do non-visual timing stimuli reduce lack of engagement?

The sixth research question investigates whether auditory and haptic timing stimuli are more emotionally arousing than visual timing stimuli. We argue that visual information in the form of a rotating clock on screen might be tiring or tedious, and therefore this research question explores the use of timing stimuli perceived through non-visual senses to compare subjective reports of emotion.

Table 1.1 shows how the research questions are distributed in the different chapters of this thesis specifying the main objectives.

Research Question	Objectives	Chapter
RQ1: Is a SoA experienced in touchless interaction? **RQ2:** What type of feedback produces greater SoA in mid-air interfaces?	• Implement a reliable gestural action using optical finger tracking. • Compare IB observed in gestural and physical actions. • Compare and contrast different types of system feedback (visual, auditory and haptic) as a response to gestural and physical actions.	Chapter 3
RQ3: Do emotions produced by odours modulate the SoA? **RQ4:** Does a positive smell increase the SoA?	• Explore elicitation of emotion (positive, negative and neutral) through odorants. • Compare IB elicited by the different emotions induced by odorants. • Validate emotion activation through self-report scales. • Assess olfactory stimulation through activation of physiological responses (skin resistance).	Chapter 4
RQ5: Can the IB paradigm be employed using a non-visual timing stimulus? **RQ6:** Do non-visual timing stimuli reduce lack of engagement?	• Develop novel timing techniques based on auditory and haptic cues that do not require visual information. • Explore whether IB is observed with audio and haptic timing cues. • Compare audio and haptic timing with traditional visual timing techniques in terms of self-reported emotion.	Chapter 5

Table 1.1 Research questions and objectives and their distribution in each chapter.

1.3 General Overview

We start our exploration by reviewing the literature on SoA and its emerging implication within HCI in Chapter 2. In Chapter 3, we explore agency in mid-air interfaces. In physical interaction (e.g., keyboards and touchscreens), it is easy to perceive that we are controlling a system as it involves touching objects (e.g., pressing a button or tapping a screen). However, in mid-air interaction where the main interplay involves gestures, agency could be challenging. Today, touchless interfaces are being employed in critical applications, in which the user is able to manipulate digital content without physically touching controls and simply mimicking the movements we would make with actual objects, for example, making a click gesture to simulate a button press (Saffer, 2008). However, even when a touchless input command is accompanied by sensory feedback to confirm an action, the fact of not perceiving any physical limit could affect our feeling of control. Inspired by recent research showing that differences in interaction techniques can significantly affect the experience of control (Limerick et al., 2015), we explore in this chapter whether users perceive agency in touchless interfaces and what kind of feedback is more suitable in this interaction modality.

To investigate this, we conducted two studies measuring IB via the Libet clock method. In the first study, we compared IB in physical and gestural input modalities preceding visual and auditory feedback. Then, in the second study we added haptic feedback (vibrotactile and mid-air) to explore what type of interaction input/feedback elicits higher SoA. In the results, we found that both physical and gestural actions elicit a binding effect only when receiving auditory or haptic feedback (i.e., a system confirmation of a touchless action) unlike visual feedback. This work was published at CHI 2017. DOI: 10.1145/3025453.3025457

Following the line of mid-air systems, in Chapter 4, we explore agency in olfactory interfaces and how emotions evoked by odorants influence IB. Olfactory interfaces are becoming increasingly popular in HCI, covering areas such as VR (Barfield & Danas, 1996) and automotive applications (Yoshida et al., 2011). Our sense of smell is often considered poor compared with other senses, and thus our interaction with technology is dominated by visual, auditory and haptic interfaces. However, olfactory information is quite powerful in evoking and modulating emotions, memories and mood, suggesting a strong potential to improve user experiences (Obrist et al., 2014).

Following evidence that the SoA is modulated by affective information (visual, auditory and somatosensory), in Chapter 4, we explore if agency is affected by a powerful sense that is strongly connected to our emotions: the sense of smell. To explore this, we conducted a study where IB was measured while subjects were presented with scents to evoke different emotions (positive, negative and neutral). Our results show that SoA increased when subjects were exposed to positive scents compared with the neutral and negative scents. These findings can provide a major benefit in the design of olfactory interfaces. For instance, presenting multisensory affective cues in form of scents might represent a positive effect towards user interfaces improving users' SoA, and increasing thus potential applications.

Chapter 5 consists of exploring novel methods to measure the SoA using different sensory modalities. The motivation for exploring alternative measures of agency arose for two main reasons: (1) In Chapter 3, we found reduced SoA for an action that caused visual feedback presented at the same time as a Libet clock was shown on screen. The Libet clock method involves relevant visual attention as it requires subjects to pay attention and report its position. Thus, presenting additional visual stimuli can produce divided attention and therefore affect measurements. This suggests that current visual timing stimuli methods to measure agency are limited in scenarios that involve relevant visual information (e.g., in VR). (2) In Chapter 4, we found that a different sense (the sense of smell) beyond the typical senses involved in HCI (vision, audio and touch) can serve as a medium to convey information and produce an effect on agency. Given that the traditional Libet clock method involves relevant visual demand, we wanted to explore whether different senses can be used to measure perception of time in the IB paradigm.

To do so, we developed two novel timing techniques based on auditory and haptic cues that provided a reference for reporting the time at which events occurred (actions and outcomes). We demonstrate that these techniques effectively offer modality variants for agency measurements in an IB task, thus addressing visual demand. This work was published at CHI 2018. DOI: 10.1145/3173574.3174115

Finally, in Chapter 6 we conclude by highlighting the main contributions of this thesis and the importance of agency measures in HCI as well as the importance of preserving user responsibility when designing user interfaces.

Chapter 2
Literature Review

2.1 The Sense of Agency

"The feeling of making something happen."
(Haggard, 2017)

The sense of agency (SoA) refers to the experience of being the initiator of one's own voluntary actions and through them influencing the world around us (Beck et al., 2017). Georgieff and Jeannerod defined this phenomenon as a "who" system that permits the identification of the agent of an action and thus differentiates the self from external agents (Georgieff & Jeannerod, 1998). The SoA has also been suggested to reflect the experience that links our free decisions (volition) to their external outcomes, i.e., a result of action-effect causality where the match between the intended and actual result of an action produces a feeling of controlling the environment (Synofzik et al., 2013), such as happens when we press the light switch and perceive the light coming on (e.g., I did that) or when we press a key on the keyboard and the computer responds with a visual effect on screen (e.g., I control this).

With these two interrelated visions of agency, Synofzik et al. drew a marked distinction between the *feeling of agency* (FoA) and the *judgement of agency* (JoA) (Synofzik et al., 2008). While the FoA is a non-conceptual feeling of being an agent based on the comparison between predicted and actual sensory events, the JoA is a conceptual interpretative judgement of being an agent or not. Studies that investigate the FoA, for example, make a direct comparison between predicted and actual action-outcome. On the other hand, studies that investigate the JoA might test whether a certain event was caused by the subject or by the computer (Synofzik et al., 2008).

The JoA has been previously explored in HCI, particularly in relation to joint action and human-robot interaction in studies in which humans and machines share a goal (Limerick et al., 2015). However, the FoA has been more commonly investigated in recent research focused on an interplay of input commands and system feedback; that is, in experiments that explore how the experience of controlling a system is given by users' perception that sensory outcomes from the system are produced by their own actions. Since in this thesis we particularly focus on an interplay of input and output channels, from Chapter 3 (where the main studies are described), we use "SoA" to refer to the FoA as a phenomenon serving to explore the action-outcome relation in HCI.

The concept of agency has been extensively investigated in fields such as philosophy, psychology and neuroscience (De Vignemont & Fourneret, 2004). A wide range of studies have provided relevant understanding of agency mechanisms in mental disorders. For example, lack of agency is associated with schizophrenia (Mellor, 1970) and delusions of control (Frith, 1992). Patients with these disorders do not feel they are in control of their own actions and sometimes their thoughts (Mellor, 1970). Indeed, studies comparing SoA in patients with schizophrenia and healthy individuals has provided relevant understanding of the brain mechanisms underlying agency (Haggard, 2017).

It has been suggested that "we experience a clear feeling (or 'buzz') of agency during everyday actions" (Haggard, 2017). Because the brain mechanisms that produce this experience are quite efficient, our SoA may be considered unnoticed. However, our SoA becomes clearer when it is disrupted. For instance, if I try to switch the light on when the room is dark, but the switch fails, I will experience a mismatch between my expectations and the actual result of my action, and therefore my SoA is lost; that is, the experience of being in control is suddenly interrupted (Haggard, 2017).

This example reflects the importance of agency experience in interaction with systems. If the experience of control is suddenly interrupted while using a certain technology (e.g., a smartphone, a car, an industrial machinery or an aircraft), the user might lose self-attribution of his/her own actions' outcomes. For this reason, the SoA is gaining increasing attention from the field of HCI aiming to advance our understanding of the role of agency experience in interactions involving technology. Developing user interfaces and interaction techniques that increase user's SoA will support an internal locus of control – a key rule for user interfaces (Shneiderman, 2005), promoting the experience that a system's outcomes result from one's own actions rather than from external factors. In the next section, we describe the two common theories that explain the origination of agency.

2.2 Origination of Agency: Predictive and Postdictive Models

Currently, two theories explain the origination of the SoA based on predictive and postdictive accounts (Synofzik et al., 2013). The predictive model relies on internally generated predictions and expectations of an action's consequences, whereby the SoA arises when matching predicted and actual sensory results (Blakemore et al., 2002). The postdictive model relies on retrospective reflection, whereby the SoA arises after perceiving the action's outcome (Wegner, 2003; Maeda et al., 2012). Here, the perception of causation (relationship between action and outcome) is a result of post-action information.

One example that supports the predictive theory is the *comparator model* (Figure 2.1) (Frith et al., 2000; Wolpert & Flanagan, 2001; Blakemore et al., 2002), which consists of a computation model that explains the motor control system. This model starts with a goal that enables a desired state. Then, a movement is generated which updates the state of the motor system and generates sensory feedback. Based on this initial information, an estimated state is generated and constantly compared with the desired state. Crucially, within the motor command stage, a predictive component uses an "efference copy" that anticipates both changes in the motor system and sensory consequences resulting from those changes.

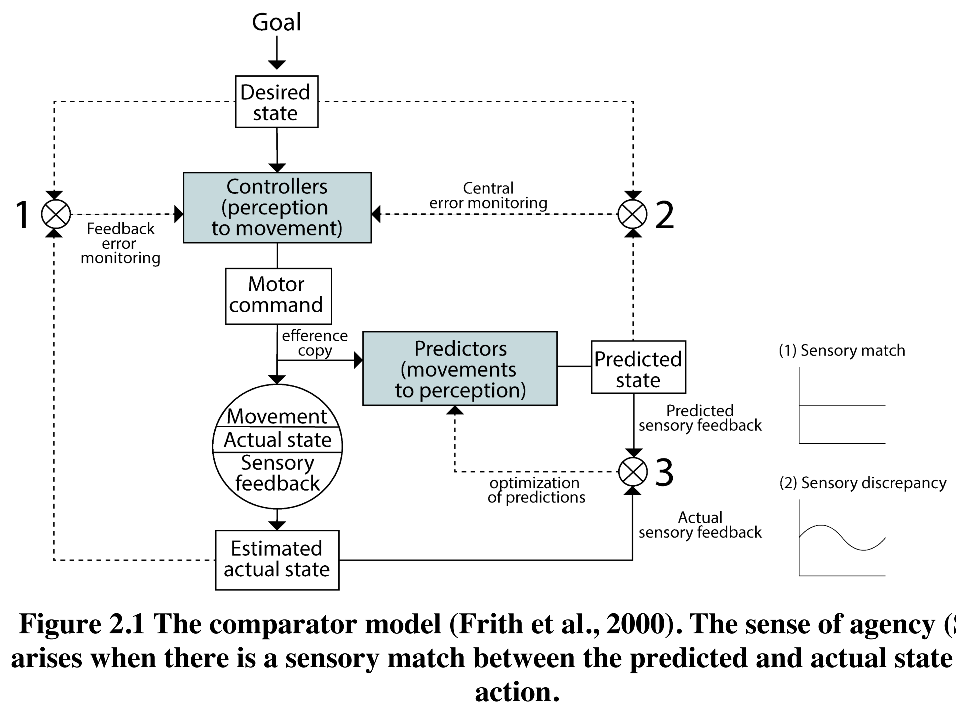


Figure 2.1 The comparator model (Frith et al., 2000). The sense of agency (SoA) arises when there is a sensory match between the predicted and actual state of an action.

Based on this information, a predicted state is generated which can then be compared both with the desired state and the actual state. According to this model, the SoA arises as a result of the comparison between predicted and actual states: if they match, we feel a SoA, and if they do not match, we do not.

On the other hand, Daniel Wegner's account suggests that the SoA arises from variable post-hoc inferences occurring not only during the action but also after the action has occurred, rather than as a result of motor preparation and cognitive anticipation. This model relies on three main principles that condition agency: *priority*, *consistency* and *exclusivity* (Wegner & Wheatley, 1999). According to this model, the SoA arises when (1) a conscious thought that precedes the action (*priority*) is consistent with the actual outcome of the action (*consistency*), and there is no other apparent cause of such outcome than one's thought (*exclusivity*) (Wegner, 2002; Wegner, 2003). This view relies mainly on the accumulation of sensory evidence about our actions.

Many studies have supported this postdictive explanation of agency. For instance, (Johansson et al., 2005) observed postdictive influence over subjects' actions based on *choice blindness*. In this study, participants were asked to visually choose one option from among others. Then, the experimenters swapped the participants' chosen option with a new one and presented this new option as their original choice. When participants were asked to explain the reason for their choice, they tried to justify why they chose the swapped option, even though it was clearly different to the original choice.

Another example is an experiment conducted by (Takahata et al., 2012) in which participants were presented with rewarding and punishing outcomes by associating auditory stimuli with positive, neutral and negative monetary outcomes. The results showed that participants attributed an action to themselves depending on the outcome condition; they tended to misattribute the action when its effect produced a negative outcome.

Although prior work found in the literature differs in its explanations about the initiation of SoA, both models (predictive and postdictive) are considered valid. Indeed, a number of studies have suggested that the SoA depends on a combination of both predictive and inferential processes (Moore & Haggard, 2008; Synofzik et al., 2013). One example is the cue integration model, which is explained in the next section.

2.2.1 Cue Integration and SoA

Prior studies have suggested that "the challenges facing the agency processing system are comparable to those facing the perceptual system" (Moore & Fletcher, 2012). The perceptual system collects a combination of cues from different sources of sensory information (including vision, touch and audition) to resolve potential ambiguities. In this line, (Ernst & Bülthoff, 2004) divided this phenomenon into two strategies i.e., *cue combination* and *cue integration*. While *cue combination* accumulates information from different sensory sources (non-redundant signals) to disambiguate uncertainty, *cue integration* integrates information from different sensory sources (redundant signals) to find the most reliable estimate by reducing its variance as much as possible. Maximum-likelihood estimation (MLE) (Kendall & Stuart, 1979) is often employed to integrate different sources of sensory information when the goal of sensory estimation is specified (Kendall & Stuart, 1979).

For instance, (Ernst & Banks, 2002) manipulated the reliability of visual and haptic information in an object size discrimination task by adding noise. They found visual dominance when the reliability of haptic information was decreased (i.e., visual information was very reliable). On the contrary, they observed haptic dominance when the reliability of visual information was decreased (i.e., haptic information was very reliable).

In line with this research, it has been proposed that the SoA is determined by the integration of various agency cues and the influence of those cues is weighted based on their reliability. For instance, (Moore et al., 2009) conducted a study showing that the influence of external cues to agency increased when the reliability of internal motoric signals was decreased (Moore & Haggard, 2008; Moore et al., 2009). This suggests that the SoA is determined not only by internal motoric signals based on perditions but also by a combination of internal signals and external cues which influence to determine the source of action is weighted by their reliability.

The cue integration model has been suggested to better explain the origination of agency in comparison with alternative explanations such as the comparator model (Frith et al., 2000; Wolpert & Flanagan, 2001; Blakemore et al., 2002), and the model proposed by (Wegner & Wheatley, 1999) which accounts apparently cannot explain illusory experiences of movement reported in previous studies (Desmurget et al., 2009).

According to (Moore et al., 2009), the presence of internal motoric cues can produce higher weighting than external cues to determine the source of action. That is, more weighted motor command signals will produce stronger prediction from the cue integration framework, resulting in illusory experiences of movement. Controversially, in the absence of such internal motoric cues, external cues become more reliable, having a higher weighting to determine the source of an action. That is, more weighted external signals can be sufficiently compelling to override internal motoric signals, resulting in experiences of not having moved although movement had actually occurred.

Vision often tends to be dominant in weighting for certain estimates, producing the experience of agency in the absence of movement. Virtual reality (VR) is an example of an environment in which visual information is relevant and can be easily manipulated. For example, participants in a study by (Banakou & Slater, 2014) falsely attributed an action (speaking) to themselves. The experiment consisted of a virtual scene in which participants saw a life-size speaking avatar from the first-person perspective (1PP) through a virtual mirror. Participants also received thyroid cartilage vibrotactile stimulation synchronized with the avatar's speech. Crucially, the movements of the avatar's body and participants' body were also synchronized to create the illusion of body ownership (the sense of "this is my own body"). The authors found that participants thought they were speaking the words when actually they were not. In a more recent VR study, it was found illusion of agency over walking in seated participants (Kokkinara et al., 2016).

In these examples, external cues (the visual feedback of the speaking avatar and vibrotactile feedback in the thyroid cartilage) receive higher weighting, and therefore contributes more to the experience, than internal cues. These findings suggest that body ownership in immersive virtual reality (IVR) that involves relevant external cues might induce illusory SoA when agency is in fact entirely absent, namely, in the absence of prediction, priming or cause preceding the effect.

The previously mentioned studies have provided relevant insights about the origination of agency to explore its modulation (e.g., through priming and IVR). Certainly, to study agency, methods to measure this phenomenon are crucial. In the next section, we provide an overview of the main methods employed to measure agency.

2.3 Implicit Measures of Agency

The most common method to assess the SoA is based on explicit judgement, obtained by simply asking subjects whether they were the agent of a certain action. However, prior work has suggested that explicit human judgement can be subject to a number of cognitive biases, and therefore, strategies have been developed to implicitly measure the SoA; one example is the intentional binding (IB) paradigm (Haggard et al., 2002), which indicates a relationship between agency experience and perception of time. In this paradigm, the level of agency can be assessed as perceived differences in time between voluntary actions and their resultant outcomes. The IB paradigm employs a subjective report of time perception from subjects using a Libet clock. Next, we describe these implicit methods to assess the SoA.

2.3.1 The Libet Clock and the Intentional Binding Paradigm

In 1982, Benjamin Libet studied the timeline regarding (i) brain neural activity, namely, the "readiness potential" (RP), (ii) the conscious experience of executing a motor movement (free will) and (iii) the actual motor movement (a wrist extension). To this end, he proposed the use of the Libet clock (Figure 2.3A), which provides a measure for the subjective awareness of free will "W" (i.e., the time at which awareness of the wish to act first appears) (Libet et al., 1983). It consists of a clock with a dot that rotates clockwise once every 2560ms (a speed approximately 25 times faster than that of a conventional clock). The marked numbers around the perimeter are thus equivalent to about 40ms each.

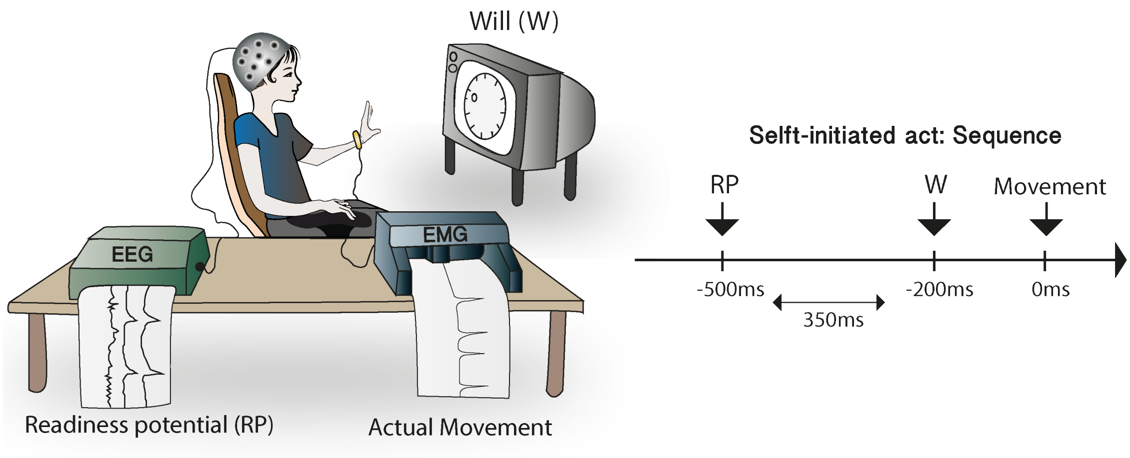


Figure 2.2 Libet's experiment (left). The readiness potential (RP), obtained by EEG, arises before the conscious awareness of free will (W) subjectively reported by subjects using a Libet clock on screen. Then, W arises before the actual wrist movement recorded by EMG (right).

During Libet's study, subjects were presented with this clock through an oscilloscope timer. Readiness potential was measured via an electroencephalogram (EEG) using electrodes placed at various points on the scalp. The action consisted of a wrist movement and was detected via an electromyograph (EMG) which recorded subjects' muscle movements through electrodes on the skin. Finally, free will (W) was measured using the Libet clock and by asking subjects to note the position of the dot when they were first aware of the urge to act (Libet, 1999; Obhi & Haggard, 2004).

The timeline of events during this experiment showed that the intention of movement is first generated by a brain process over which we have no control, as at that moment we are not consciously aware. Subsequently, the subjective experience of free will emerges and finally the actual motor movement occurs (see Figure 2.2).

With this method, Libet provided important evidence on the origination time of conscious will. His view suggests that the volitional process (i.e., RP occurrence) arises unconsciously at about 500ms before the actual action; however, the subjective experience of free will (i.e., reported by subjects using the Libet clock) emerges about 200ms before the actual motor movement (see Figure 2.2). This suggests that free will does not initiate a voluntary act, but it could control the performance of the act (i.e., it can veto the act) (Libet, 1999; Schultze-Kraft et al., 2016). Some researchers have suggested that free will could be better described as "free won't" because this process seems to have more to do with the decision to execute an action or not before the action itself occurs (Obhi & Haggard, 2004; Schultze-Kraft et al., 2016). In summary, Libet's finding suggests that free will follows the onset of RP rather than precedes it. However, this has been subject of debate within the literature (Danquah et al., 2008).

Subsequently in 2002, Patrick Haggard adapted the Libet clock to incorporate it in the IB paradigm (Haggard et al., 2002). He used the Libet clock to measure the temporal binding between a voluntary action (button press) and its sensory outcome (a tone), demonstrating that actions and outcomes reciprocally attract each other in subjective awareness. As shown in Figure 2.3(b) –right, subjects perceive delayed awareness of a voluntary action (action binding) whilst anticipated awareness of its outcome (outcome binding) relative to single judgement errors. That is, people tend to perceive voluntary actions and their outcomes as close in time (Haggard et al., 2002; Ebert & Wegner, 2010). The summation of these two components (total binding) is thus associated to the experience of agency. The higher the total binding, the higher the SoA (Ebert & Wegner, 2010; Moore &

Haggard, 2010). A Libet clock on screen (Figure 2.3(a) – left) is used to measure subjects' time perception. Subjects report the clock position (the dot location) at the moment of their voluntary action (a button press) and its outcome (the resultant tone).

As shown in Figure 2.3(b), two baseline and two active conditions are employed to calculate action and outcome binding. In baseline conditions, only one event occurs – either action or outcome. In active conditions, both action and outcome occur. During the task, both actual time (dot position on the Libet clock logged by the system) and perceived time (dot position on the Libet clock reported by subjects) of the action and outcome are recorded.

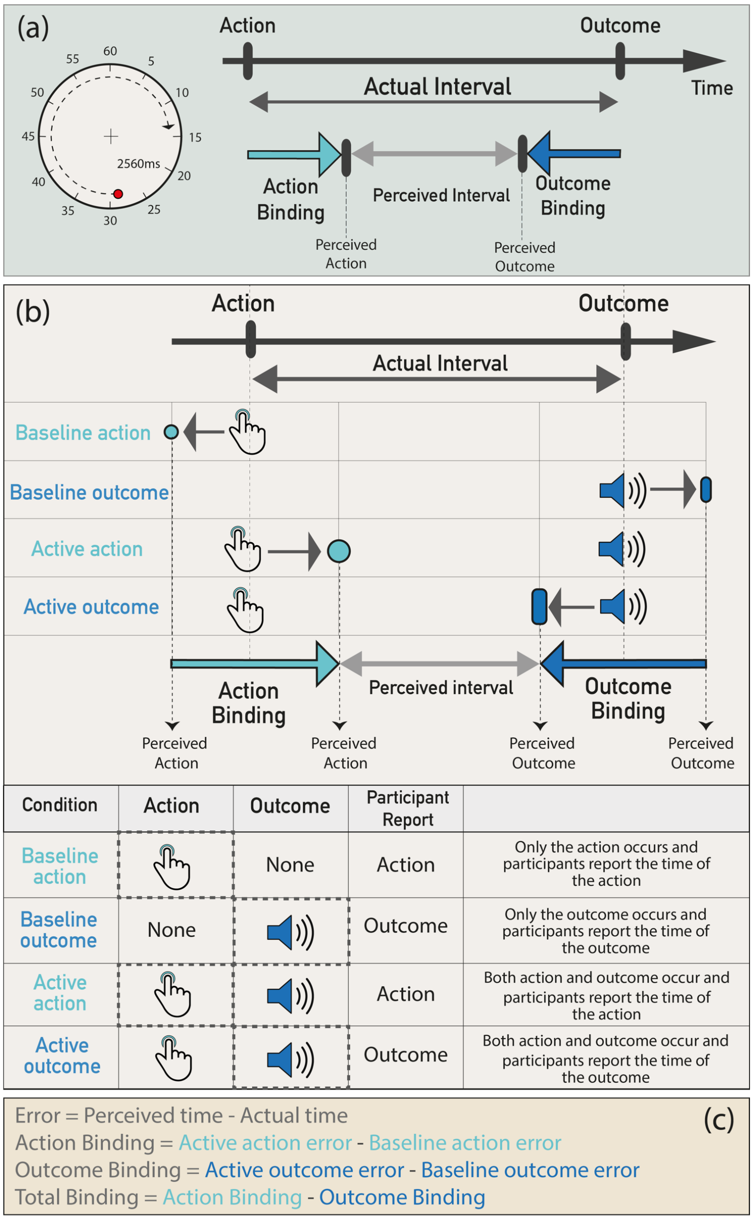


Figure 2.3 The intentional binding (IB) paradigm. (a) left: The Libet clock, right: The IB effect. (B) Measurement conditions (baseline and active). (c) IB calculation formulas relative to single-event judgement errors.

The errors are calculated using the difference between perceived and actual time. Following this, IB is calculated through the formulas shown in Figure 2.3(c).

This temporal binding can be depicted as the bi-directional limitation of Bayesian causal inference (Eagleman & Holcombe, 2002): "If two events occur closer together in time, it is more likely they will be perceived as causally related. Therefore, if two events are known to be causally related, they are more likely to occur closer in time" (Hume & Beauchamp, 2000; Buehner, 2005). The IB effect is generally observed when actions are voluntary (e.g., self-paced voluntary keypress); moreover, for involuntary actions (e.g., twitches caused by transcranial magnetic stimulation (TMS)) the opposite effect is observed; that is, temporal repulsion rather than attraction is observed between a passive action and its outcome. Nevertheless, a recent study revealed outcome binding for involuntary actions based on learning and association (Khalighinejad & Haggard, 2016).

The IB paradigm has been suggested to provide a viable implicit measure of the SoA (Moore & Haggard, 2010; Moore & Fletcher, 2012). Since explicit judgement of agency can be subject to cognitive biases (Chambon et al., 2012; Sidarus et al., 2013; Haggard, 2017; Sidarus et al., 2017), some researchers have compared and contrasted implicit agency using the IB paradigm with explicit agency via self-report (Obhi & Hall, 2011). One limitation of the IB paradigm, however, is that it requires significant visual attention as it relies on subjects' observation of the Libet clock, which is usually small in size to keep subjects' attention. For example, in the study by (Coyle et al., 2012) it was "100 pixels in diameter and displayed on a screen with a resolution of 1920 x 1080 pixels". An alternative implicit measure of the SoA is the *interval estimation* method (Ebert & Wegner, 2010), which does not requires relevant visual information.

2.3.2 Interval Estimation

The interval estimation method is also based on the idea that actions and outcomes are shifted towards each other, and shorter perceived intervals between action and outcome refer to a higher SoA (i.e., IB). However, this method consists of simply asking subjects to estimate the time interval in milliseconds between a voluntary action and its outcome (which is randomly varied). The error estimation is calculated by the difference between actual and reported time in milliseconds. The mean error is thus associated to IB; i.e., an underestimation of the intervals refers to higher SoA (Ebert & Wegner, 2010). Crucially, during a training stage, in which subjects are allowed to practice their interval estimation with the feedback of the actual intervals, they are told that the possible delays between action and outcome have a large resolution, whereas during the actual experiment only reduced fixed intervals are presented. For instance, in the study by (Ebert & Wegner, 2010; Coyle et al., 2012), the training stage involved delays ranging from 50ms to 950ms in intervals of 50ms (i.e., 50ms, 100ms, 150ms, 200ms, etc.), while in the actual experiment only three fixed intervals are presented (100ms, 400ms and 700ms) in a counterbalanced order. However, different ranges and fixed intervals have been employed depending on the aim of the study (Caspar et al., 2016).

The benefit of this method is that it does not involve significant visual attention (as the Libet clock does) and requires only one measurement rather than two baseline and two active blocks of each action and outcome conditions (see Figure 2.3). This makes it suitable for studies involving a larger number of experimental conditions. However, the interval estimation method does not allow distinction between action binding and outcome binding. In other words, it is not possible to observe if the task produced higher anticipation of the outcome or a late awareness of the action. Having two separated values of action and outcome binding could be more informative for HCI, giving further evidence related to user input and system feedback. However, depending on the main objective of each study, both the IB paradigm and interval estimation can be employed as both methods have been extensively used within the literature.

Moreover, apart from time perception, another approach that has been suggested to be related to the SoA is sensory attenuation. Prior studies have shown that changes in this phenomenon can be a marker of agency. Next, we present an overview of these studies.

2.3.3 Somatosensory Attenuation

Somatosensory attenuation (SA) refers to the softening of tactile sensations during *self-touch*. This effect serves as a defence mechanism in humans and is generated by the central nervous system to distinguish between self-related signals (e.g., your own fingers scratching your neck) and non–self-related signals (e.g., a spider crawling up your neck) (Kilteni & Ehrsson, 2017). That is, since external signals can represent potential threats, they must be clearly distinguished from self-related signals. For instance, when we touch our arm with our own hand, the touch feels less intense than an identical touch generated by another person. This effect results from a brain prediction (the so called efference copy) of the self-generated contact between our hand and arm, attenuating the expected sensation (Weiskrantz et al., 1971; Blakemore et al., 1999; Blakemore et al., 2000).

Due to the fact that SA is related to the *self*, some studies have suggested that an attenuation of tactile perception can be a marker of agency (Blakemore et al., 1999). That is, this attenuation should be stronger when events are self-attributed (e.g., it was me) than when they are misattributed (e.g., it was not me). In this line, studies have explored whether lower intensity pain ratings (induced by heat or electrical stimulus) are associated with a greater IB effect. Although they found that SA is a result of free choice compared to instructed action (i.e., the intensity of the sensory consequences of voluntary action is lower), no clear effect on binding was found (Beck et al., 2017; Borhani et al., 2017).

Indeed, in a study by Kilteni et al., a significant correlation between the strength of body ownership and the degree of *somatosensory attenuation* was observed. However, in conditions where *somatosensory attenuation* was modulated, a SoA was always experienced (Kilteni & Ehrsson, 2017). This finding suggests that attenuation occurs only for sensory predictions related to one's own body and not for sensory events that are caused by motor actions. Therefore, somatosensory attenuation is unlikely to be a marker of agency, and thus "the exact relation between *sensory attenuation* and sense of instrumental agency remains unclear" (Haggard, 2017).

Based on this evidence, in this thesis we explore agency by using the view related to perception of time rather to sensory attenuation. Indeed, recent studies that have investigated agency in HCI are mainly based on experiments that test subjects' perception of the time that elapses between input modalities and system feedback. We present an overview of these studies related to interaction with technology and user interfaces.

2.4 Explicit Measures of Agency

Measures of explicit agency are based on subjective judgement, commonly obtained by simply asking a subject whether he/she was the agent of certain action or not (e.g., "did you do that?") (Haggard & Tsakiris, 2009), or subjective scales (e.g., rate your level of agency on a scale from 1 to 7). However, research on agency and decisions (Synofzik et al., 2008), has suggested that "explicit measures of the SoA are subject to a number of cognitive biases and are highly sensitive to task demands" (Khalighinejad & Haggard, 2016). In other words, people's decisions are often influenced by unconscious information, and the way we think we decide is different from the way the brain actually decides for us. Prior studies have provided evidence of these biases in human judgement, by investigating the effect of subliminal primes on people's decisions (Chambon et al., 2012; Sidarus et al., 2013; Sidarus et al., 2017). Here, people tend to report more SoA when their decisions are actually influenced by external cues than when they resist an influencing prime (Wenke et al., 2010). Similar effects are observed in *choice blindness*, whereby people tend to retrospectively invent an experience of their own decision when this was clearly not the decision the brain originally made (Johansson et al., 2005). Crucially, these biases have also been found when comparing implicit and explicit measures of agency, suggesting that self-reports and IB may operate differently. For instance, (Strother et al., 2010) found that self-reports reflect reduced SoA while implicit measures indicate a high IB effect, suggesting that explicit agency and IB do not share a common mechanism.

There exists a salient conflict between explicit and implicit measures of agency, especially when exploring agency in more complex and visual tasks such as in VR environments. The IB paradigm using the Libet clock mainly consists of simplistic desktop action/outcome tasks (e.g. button presses and tones), and can require relevant visual attention. This is a challenge in VR environments where users are exposed to visual information constantly and actions are more complex (e.g., full-body movements), making it difficult to implicitly assess agency and preventing actual applications. Therefore, studies on agency using VR setups are usually limited to using self-report questionnaires as a measure of the SoA.

While the *interval estimation* method (Ebert & Wegner, 2010) could address this limitation (an implicit method that does not involve significant visual attention), its lack of distinction between action binding and outcome binding might be less informative for the action–feedback interactions common in HCI. That is, having these two measures provides broader evidence on how system modalities in HCI affect users' SoA.

In prior work, using the Libet clock method, (Limerick et al., 2015) found reduced SoA for speech input reflected in low outcome binding but not in action binding. In another example, in Chapter 3, we found no differences in action binding for gestural or physical input commands but found that outcome binding was higher for haptic feedback compared with visual feedback in touchless interaction.

Moreover, although the Libet clock has been considered a viable method to implicitly measure the SoA, it also involves limitations related not only to visual demand but also to tediousness, since a rotating stimulus might be monotonous due to the number of trial repetitions (usually 30), thus producing loss of engagement. This prevents more complex setups such as VR environments.

In light of this evidence, in this thesis we focussed on implicit measures of agency by measuring the IB effect using the Libet clock method, considering it more informative for HCI to obtain separate values for action and outcome binding. Moreover, we explored solutions to address current limitations of the Libet clock, such as visual demand and tediousness, by exploring timing stimuli through different senses.

2.5 Agency in Human-Computer Interaction

Due to the ubiquity of our interaction with systems (e.g., computers, smartphones and tablets) for work or leisure purposes, we usually do not think about our SoA during the interaction, and it may be unnoticed (Moore, 2016). However, a clear example that highlights the importance of our SoA in HCI is when this experience is disrupted. When there is a mismatch between expectations and the actual sensory feedback from the system, the user experiences a sudden interruption in the feeling of control. This can negatively affect acceptability (Berberian, 2019) and usability (e.g., poor game controllers may cause frustration (Miller & Mandryk, 2016)).

For this reason, the SoA is gaining increasing attention from the field of HCI. Developing interaction techniques that increase user's SoA will provide the feeling of "I did that" as opposed to "the system did that", supporting thus a feeling of being in control.

With the availability of methods to quantify the experience of agency, recent studies have provided evidence of agency modulation by interactions paradigms involving input commands and system feedback. Input modalities and system feedback play an important role in the SoA as they are crucial aspects to build the communication dialogue in HCI (Hornbæk & Oulasvirta, 2017).

2.5.1 Input Commands and System Feedback

"*A computer interface facilitates control. It provides a set of mechanisms by which a human can drive the belief of a system about a user's intentions towards a desired state over a period of time*." (Williamson et al., 2009)

Input modalities serve to translate user's intentions into state changes within the system, while system feedback informs the user about the system's current state. As shown in Figure 2.4, the separation between user's intentions and computer state changes is known as the "gulf of execution" while the mismatch between the computer's actual state and user's expectations is known as the "gulf of evaluation" (Norman, 1986). The goal of HCI is to bridge these gaps (Limerick et al., 2015).

During recent years, research in HCI has introduced a wide range of new interaction techniques involving input modalities beyond the traditional mouse & keyboard interaction. For instance, speech control is becoming increasingly popular through commercial products such as Apple Siri, Amazon Echo and Microsoft Cortana. Speech input gives users the capability to control devices from a distance with high quality recognition rates (e.g., 97.3%). In another example, body–touch input is becoming popular to control smartwatches. Today, the use of smartwatches is expanding, but due to the so called "fat finger problem" (Siek et al., 2005), touch input on a size-limited screen is challenging, and researchers are introducing a "Skinput" modality (Harrison et al., 2010) to overcome this problem. For instance, by tapping and sliding the finger against the arm (Zhang et al., 2016; Sridhar et al., 2017).

These new kinds of input modalities enable distinct ways of bridging the gulf of execution as they involve different types of action initiation and sensory feedback (Limerick et al., 2015), and they can thus affect the experience of control. In light of this, HCI researchers have investigated how emerging input modalities influence the SoA.

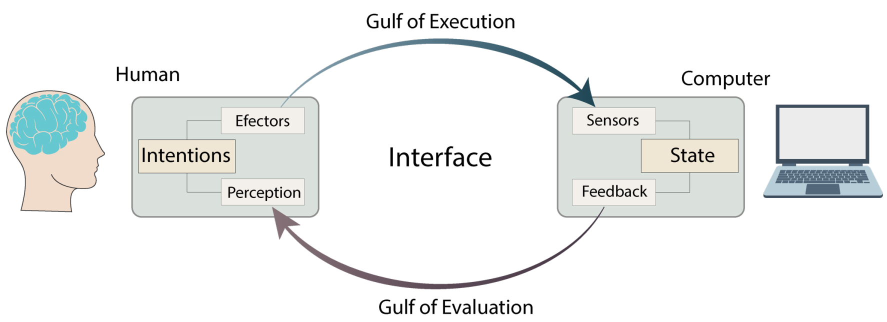


Figure 2.4 Interaction loop input–feedback in HCI highlighting the gulf of execution and the gulf of evaluation. Diagram based on (Norman, 1986; Williamson et al., 2009; Limerick et al., 2015).

For instance, Coyle et al. compared Skinput (Harrison et al., 2010) with traditional keyboard-based button press input to explore "what happens when the input modality changes" (Coyle et al., 2012). Skin-based input consisted of a small piezoelectric microphone placed on participants' forearm so that a tap on the skin close to this sensor was recognized as a "button press" action. Both action modalities – Skinput and button press – were followed by audio feedback in response (a beep) and participants' SoA was measured using the IB paradigm. Their results showed a significantly higher IB effect in the Skinput condition, suggesting that skin-based input elicits greater SoA than typical keyboard input. This finding suggests that a tap on the skin could be perceived as more responsive compared with a traditional button press.

Possible explanations of increased SoA for Skinput modality include that (1) it is a self-directed action that produces higher congruency between actual and internally predicted action–outcome, (2) it constitutes more meaningful multisensory feedback that involves self-touch (integration theory) and (3) there is a possible relationship between increased activity within the motor systems for both self-related actions and agency. For the field of HCI, these findings can support applications for on-body interfaces such as skin electronics (Wang et al., 2018) and bio-sensing research that aims to use the user's skin as an "interactive canvas" (Harrison et al., 2011).

In the same line of exploring different input modalities, Limerick et al. compared speech-based input with traditional button press input (Limerick et al., 2015). Speech input consisted of asking participants to say the word "go" (voice command) as an action. Both input modalities – voice and button press – were followed by a beep outcome, and IB was measured. Their results showed reduced IB for the voice command, suggesting that speech input modality elicits lower SoA than traditional button press input. This finding interestingly suggests that this low feeling of control might contribute to the low uptake of speech interfaces for interactive applications despite their popularity and the availability of high accuracy voice recognition (e.g., 97.3% recognition rate).

This research in HCI has provided interesting evidence that changes in interaction techniques can significantly affect the user's experience of control. Limerick et al.'s research suggests that a system that evokes a low SoA will discourage users from using it, preventing widespread use of the system. On the other hand, the research from Coyle creates a large opportunity for on-body interaction systems. We need a similar understanding of the SoA for other interaction techniques in order to improve user interface design and thus enable wider uptake of systems.

In another example, (McEneaney, 2013) executed a series of experiments to demonstrate that the experience of agency not only applies in physical situations but also in HCI. They focused on answering the following question: “Are agency effects observed in desktop computing environments typical of HCI?”

They based their studies on measuring perception of click responses through visual on-screen stimuli and auditory feedback to compare human-initiated actions with computer-controlled actions. Their results showed that an agency effect exists in typical HCI desktop computer environments, supporting the claim that user perception of on-screen events depends on agency cues. However, they also found that the perception in time of participants differed depending on whether an auditory effect followed a machine or human-initiated click action.

2.5.2 Application of Agency Measures in Virtual Reality

Prior research has explored agency in more complex actions (beyond desktop environments) using explicit judgements. These studies have revealed illusory agency in IVR using head-mounted displays (HMDs) (Gonzalez-Franco & Lanier, 2017), suggesting that people may attribute an action to themselves (i.e., illusory agency) even in the absence of key aspects of agency experience (i.e., prediction, priming or cause preceding effect). Immersed in virtual scenarios accompanied by visuomotor synchronous conditions to create a strong feeling of body ownership of an avatar seen from 1PP, participants self-reported agency of actions performed by the avatar, that were not performed in reality.

According to the cue integration model, the visual information shown in VR provides stronger external cues (it is very reliable), and therefore contributes more to the experience, than internal motoric signals. This generates the opportunity to provide the user with experiences that are close to those in reality, contributing to the quality of interaction (which can have a major benefit in VR training simulators). IVR has a strong potential to produce both psychological and physiological responses by inducing the feeling of body ownership. For instance, it can cause changes in body representation (Normand et al., 2011; Kilteni et al., 2012; Banakou et al., 2013) and interpersonal attitudes (Peck et al., 2013) or affect psychological states (De la Peña et al., 2010). This suggests that there is huge room for studying agency by taking advantage of VR environments. Indeed, studying agency in IVR can be crucial, as in these scenarios, users commonly pose a virtual representation of their own body (avatar), often producing action misattributions due to delays or tacking issues common in tasks involving touchless interaction (e.g., gestural actions).

In this line, prior attempts have been made to explore agency in IVR. For example, (Kong et al., 2017) investigated if mere observation of a virtual avatar's movements can elicit implicit SoA by inducing the feeling of body ownership. However, their setup is a replica of a desktop IB task (using the traditional Libet clock), which involves visual demand and thus prevents actual VR applications. Nonetheless, their results suggest that the VR experience led to a stronger binding effect and that this effect may differ from explicit judgement of agency.

However, although this finding opens opportunities to investigate implicit measures of agency in IVR, further research is needed to develop suitable methods to assess implicit agency in more visual scenarios and more complex tasks such as gestural actions.

2.6 Touchless Systems

Interactive systems that use a touchless approach typically require no physical contact with a surface or object, avoiding the constraints of ordinary interaction paradigms (e.g., mouse & keyboard). These systems often rely on gesture-tracking technologies to detect mid-air gestures. The most common approaches rely on optical technology (Zhang, 2012; Taylor et al., 2016) and EMG (Nuwer, 2013; McIntosh et al., 2016). However, more recent devices offer higher resolution of gesture-sensing based on radar (Lien et al., 2016) and sonar (Nandakumar et al., 2016) technologies.

Taking advantage of their properties, touchless systems are being deployed to perform interactions in many critical situations such as surgery and dashboard control. Touchless manipulation of medical images allows surgeons to maintain the sterile environment required in surgery, without the help of assistants (O'Hara et al., 2014). Another example is driving, and today there are many dashboard panels that allow users to control car elements from a distance (Asley, 2014). The use of gesture recognition and proximity to manipulate car controllers releases the user's visual channel, promoting safer driving.

Although mid-air, gesture-based devices may have a wide range of capabilities, most radar, sonar or optical tracking-based gestures typically share common characteristics with mice and tablets. In both approaches, the main interplay consists of pointing and clicking actions (Wigdor & Wixon, 2011). In these mid-air gesture interaction systems, pointing is represented by hand tracking, and clicking is represented by "activation gestures" (Wigdor & Wixon, 2011), which define the intention to communicate with the system (Golod et al., 2013). These gestures must be natural and intuitive, but uncommon, so that they are not performed accidentally (Cadoz, 1994). Following this, the user expects a confirmation of the activation, namely, a perceptible response from the system. This refers to "system attention" (Baudel & Beaudouin-Lafon, 1993), which is attained through multisensory feedback. Feedback is important in touchless systems as there is no physical contact with an object (e.g., floating images or virtual keyboards). However, it is not necessary to physically touch an object to have the perception of a button press if it is associated with an effect in response.

2.6.1 Visual, Audio and Haptic Feedback

Touchless interaction can be helped by sensory effects in order for the user to perceive system attention. This can be achieved by providing users with multisensorial feedback, i.e., visual, auditory and haptic (Golod et al., 2013). For instance, (Freeman et al., 2016) added light, audio and tactile displays to help users know "where to gesture". (Markussen et al., 2014) implemented a gestural typing system assisted by visual feedback through a virtual keyboard. (Liu et al., 2015) added visual hand-cursors on screen to make users know the state of the bare-hand postures and gestures, and (Wu & Rank, 2015) explored different audio feedback designs for hand gestures to encourage immersion in games. In a later work, they found that in-air gestures with responsive audio feedback leads to higher immersion and enjoyment in video games (Wu & Rank, 2015). Finally, (Müller et al., 2014) developed a technique to "touch" and manipulate sound in mid-air by combining audio, visual and tactile feedback.

A common criticism of touchless systems is that users lack haptic feedback for action confirmation. However, mid-air haptic feedback is a recent technique to make the user aware of system attention in touchless interaction. Airwave (Gupta et al., 2013), UltraHaptics (Carter et al., 2013) and AIREAL (Sodhi et al., 2013) are examples of emerging systems that can provide this missing tactile feedback in mid-air with bare hands. This technology allows users to perceive tactile sensation even in the absence of physical objects. Based on this approach, (Monnai et al., 2014) proposed a system to interact with floating images, using not only visual feedback (through light beams), but also mid-air haptic feedback through ultrasound in order to create the sensation of touching a virtual screen. In a more recent work, (Makino et al., 2016) introduced a system to clone real objects into virtual ones. It consisted of floating images that replicate the haptic properties of real objects using ultrasound, providing realistic touch interaction in mid-air without wearable devices.

The above examples represent complex systems of touchless input commands with different kinds of feedback. However, the role of agency experience during interaction with these systems has not been investigated. In other words, it is unclear if adding tactile feedback helps users feel a SoA when interacting with touchless systems.

Another field in which the SoA has recently gained attention is artificial intelligence (AI). Today, many intelligent systems are automated, implying that actions are performed by computers and machines rather than by users, which can significantly affect the experience of control. In the next section, we present an overview of research involving SoA and automation, highlighting the effect of assisted interaction on users' responsibility.

2.7 Agency and Automation

"The increasing level of automation tends to distract operators from action outcomes, decrease their sense of control and therefore disrupt their overall performance."
(Berberian, 2019)

Automated systems can make our life easier. For instance, autonomous driving and automation aids in aviation help the operator to take control and make decisions. However, the intervention of increasing automation between operators and systems means that users lose details of the interaction, decreasing their feeling of control, which raises the question, "Who is in control now?" (Berberian et al., 2012).

Studies have suggested that although the feeling of control can be affected by automation levels, giving assistance improves user performance, which in turn produces a positive effect on the experience of agency (Wen et al., 2015; Inoue et al., 2017). This suggests that SoA increases with better performance even when actions are assisted (e.g., even when several commands were not executed). However, giving assistance during interaction should be carefully designed because high levels of automation can also significantly reduce the SoA. This is due to the complexity of the cooperation process between computers and operators. In other words, “the cognitive coupling between human and machine remains difficult to achieve” (Berberian, 2019).

With the aim of exploring this coupling, prior studies have measured agency in computer-assisted tasks. Measuring the feeling of control can give relevant insights on how to evaluate and design automated devices that improve user performance without significantly reducing the SoA.

Coyle et al., 2012 explored the effect of different levels of assistance on subjects’ SoA by measuring IB via the interval estimation method. The experiment was a goal-directed computer task that consisted of clicking a target on screen. The levels of assistance were provided using a “gravity algorithm” that attracted the mouse pointer to the target with different levels of “gravity” to modulate how easy it was to hit it. For instance, a high assistance condition led to the pointer moving quite fast towards the target, thus allowing it to be clicked more easily. The researchers found that a mild level of assistance did not break the SoA. However, medium and high assistance levels significantly reduced this experience, suggesting that if the task is highly automated, the SoA is reduced (producing misattribution) but that there may exist a sweet spot at which a computer can help users without significantly decrementing agency.

In another example, (Berberian et al., 2012) conducted an experiment involving a computer simulation of flying an aircraft with various degrees of autopilot assistance. They measured agency using both IB (via the interval estimation method) and explicit reports. The task consisted of asking participants to decide, implement and engage a command to resolve a flight conflict (avoid crashing into another aircraft). The levels of assistance included conditions in which the participants had full control to resolve the conflict (no automation), in which they made only some decisions and in which the task was fully automatic. The results of the study showed that IB was modulated by levels of automation, with increasing automation leading to a decrease in the SoA. This result also correlated with explicit judgements of agency. These findings suggest that high automation levels distract users from action outcomes, decreasing the sense of control and affecting the overall performance.

Automation has also been suggested to be related with system acceptability. In a later study, using a similar aircraft supervision task, Goff et al. studied the effect of providing information cues on acceptability and SoA during interaction with automated systems.

These cues informed the user about “what the system is about to do” to alleviate the unpredictability of automation. They found that additional information about the system’s intentions increases acceptability and SoA, but this information should be displayed in an appropriate time window to provide a correct sense of control (Le Goff et al., 2018).

In a more recent work, (Berberian, 2019) suggested that research on agency can provide useful measures to explore agency-system interaction that designers could employ to develop more acceptable automated interfaces that support a feeling of control.

Certainly, automation can be beneficial for HCI, as giving some level of assistance to the users can improve their performance without negatively affecting the sense of control. However, an appropriate level of assistance should be carefully designed in each task. This is because the SoA has been suggested to underpin the concept of responsibility in human societies (Haggard & Tsakiris, 2009). That is, our sense of being an agent is not only related to executing a motor action but also to knowing “the nature and quality of the act” (Haggard, 2017). Legal systems assert that healthy adults are consciously aware of their intentions and the consequences of their acts. Therefore, it is important that automated systems give users the appropriate feeling of control in order to preserve the feeling of responsibility (especially in critical situations such as driving and aviation). In other words, it is important that systems let users clearly experience what they are doing.

Indeed, recent studies have suggested that autonomous vehicles will be on our roads in the future, and research has emerged to explore how autonomous cars should “morally” act in a critical situation, aiming at developing new regulations for autonomous vehicles.

For example, the Moral Machine (Awad et al., 2018) is a crowdsourcing experiment, in which data was collected from millions of people around the world about hypothetical moral decisions based on collision scenarios in autonomous vehicles. Subjects were presented with two possible situations (illustrated on screen) where an autonomous car with a sudden brake failure should take an action to either stay on course or swerve. Staying on course would result in the death of one group people, and swerving in the death of a different group. Crucially, during the experiment, the gender, age, size, social status, number, etc. of persons were varied in each group, and subjects were asked to choose the outcome they found preferable.

With this experiment, the authors collected 39.61 million decisions from 233 countries and found that most people showed a preference for 1) sparing human lives, 2) sparing more lives and 3) sparing young lives. Since this study was conducted using a crowdsourcing model, the authors collected individual variations in users' preferences depending on demographic information (e.g., cultural and economic variations between countries). For instance, they found that subjects from collectivistic cultures that emphasize respect to older people showed weaker preferences for sparing younger characters. Similarly, preference for sparing female characters was stronger in countries with better health and survival prospects for women. However, this study was not based on a 1PP. That is, the results were obtained based on the car's decisions rather than subjects' own actions and outcomes.

In light of this research, (Uijong et al., 2019) conducted a study to predict sudden decisions in a VR driving simulation using a 1PP setup. The aim of this research was to provide potential insights for autonomous vehicle guidelines. The study consisted of tasks in which subjects decided between falling down a cliff or colliding with obstacles. Crucially, in a control condition, obstacles consisted of trees, whereas in an experimental condition, obstacles consisted of pedestrians. In the results, the authors found that personality (e.g., psychopathy and impulsivity traits) helped to predict subjects' decision-making in extreme situations (when choosing between preservation of self or others).

Similarly, (Faulhaber et al., 2019) explored moral dilemmas in VR in which participants decided between self-sacrifice and colliding with obstacles consisting of different human-like avatars with a variety of ages and group sizes. Their results validated a utilitarian decision-making approach consisting of "sparing the highest number of avatars possible with a limited influence by the other variables".

These studies show the importance of studying and modelling human decision-making in order to start crafting guidelines for autonomous driving and preserve moral responsibility. Particularly, research in moral judgement has highlighted the role of emotions in human decision-making (Choe & Min, 2011). However, while further research is needed to explore in depth the effect of emotions on shared agency between humans and machines in autonomous systems, there is a wide range of research linking human agency and emotions. In the next section, we summarize this research, particularly focusing on the sense of smell, which has been recently included in interactions while driving.

2.8 Agency and Emotions

The self-attribution process of the SoA (e.g., I did that) is influenced by affective information (Bradley, 1978; Greenberg et al., 1992; Bandura, 2001, 2002). Prior studies have revealed that agency experience is modulated by the valence of sensory cues. That is, people tend to attribute positive outcomes to their own actions (self-attribution), while negative outcomes are attributed to external agent. In other words, people take credit for positive events and blame external factors for negative ones (the self-serving bias (Babcock & Loewenstein, 1997; Mezulis et al., 2004)).

Takahata et al. (Takahata et al., 2012) primed subjects with rewarding and punishing outcomes of actions by associating auditory stimuli with positive, neutral and negative monetary outcomes. They found that participants exhibited higher SoA when positive outcomes (monetary gains) occurred than when negative outcomes occurred (monetary losses). Meanwhile, Yoshie and Haggard (Yoshie & Haggard, 2013) manipulated the emotional valence of action outcomes with negative or positive emotional vocalizations (Sauter et al., 2010) or neutral tones. They found that SoA was reduced for negative compared to positive or neutral outcomes. For their part, Christensen et al. (Christensen et al., 2016) investigated the influence of action outcome valence (modulated by emotional human vocalisations) on prospective and retrospective components of SoA. They found that positive outcomes enhanced the retrospective agency for unexpected outcomes. In another example, Beck et al. (Beck et al., 2017) found that having control over negative somatosensory outcomes (induced by painful heat or electrical stimulus) increases SoA.

On the other hand, Aarts et al. (Aarts et al., 2012) explored affective priming through visualization of emotional pictures (Lang, 2005). Unlike the above examples, here the emotional cue was not presented as an action outcome but at the beginning of an IB task. They found that positive reward signals via brief exposure to positive pictures enhance SoA, unlike neutral pictures.

2.8.1 Smell and Emotions

Prior studies have suggested a close link between olfaction and affective information. Odours not only evoke strong experiences of pleasure or displeasure (Ehrlichman & Bastone, 1992) but also modulate mood (Warrenburg, 2005), attention (Tham et al., 2009; Keller, 2011), stress (Motomura et al., 2001; Atsumi & Tonosaki, 2007) and memories

(Herz & Cupchik, 1995). Different scents have been shown to elicit specific physiological responses or emotional states. For example, lemon is linked with arousal (Dong & Jacob, 2016) while lavender is considered a relaxing scent (Motomura et al., 2001). Lemon odour has also been suggested to have antidepressant properties (Komori et al., 1995) while lavender and rosemary decrease cortisol levels in saliva (Atsumi & Tonosaki, 2007). Lavender scent is associated with happiness while acetic acids are linked to anger and disgust elicitation (Vernet-Maury et al., 1999).

The olfactory system is deeply linked to areas of the brain that regulate emotions (Zald & Pardo, 1997; Soudry et al., 2011). For that reason, emotions evoked by odorants are very strong. For instance, it has been suggested that "odour-evoked memories are more emotional than memories evoked by other sensory stimuli" (Herz & Cupchik, 1995) and that people who have lost their sense of smell become more depressed than people who have lost their vision (Smith, 2015). While the sense of smell is often considered a poor sense (Shepherd, 2004), emerging research interestingly suggests that we use it more than we actually think. For example, a study revealed that humans have scent tracking abilities like dogs (Porter et al., 2007) and that emotions can be communicated via the olfactory channel so that we can smell someone's fear (De Groot et al., 2014).

2.8.2 Olfactory Interfaces

Although our everyday activities involve five basic senses (taste, smell, vision, sound and touch) that create compelling experiences, memories and awareness of the environment (Franklin et al., 2005) (e.g., having a coffee with a friend), our interaction with technology is dominated by visual, auditory and, more recently, haptic I/O channels. However, recent research in HCI is pursuing multisensory integration for user interfaces that also involve olfaction (Kaye, 2004; Dmitrenko et al., 2017) and taste (Vi et al., 2017; Vi et al., 2017).

Olfactory stimulation has particularly gained attention in many application contexts, for example, in-car scenarios (Yoshida et al., 2011). In this line, (Dmitrenko et al., 2017) explored odour as an information medium by mapping scents onto messages from a car. For instance, the "slow down" message was strongly associated to lemon odour and "fill gas" to peppermint odour. These olfactory messages allow drivers to receive information from the car while other senses are engaged with additional information (e.g., listening to the radio and focusing on the road). For their part, (Yoshida et al., 2011) explored olfactory stimuli to prevent drowsy driving and thus fatal car accidents. They found that peppermint fragrance effectively induces wakefulness and alertness. In another example, (Baron & Kalsher, 1998) found that lemon scent improves drivers' alertness and mood. Smell notification systems have been even patented by car companies such as Ford (Kolich, 2013).

Odours also enhance the sense of presence (Barfield & Danas, 1996) and realism (Mochizuki et al., 2004) in VR, and the presentation of scents leads to an increased sense of reality and relevance (Ghinea & Ademoye, 2012). For instance, a study has shown that tactile, olfactory and auditory cues produce more sense of presence and memory than the use of visual details alone in an environment (Dinh et al., 1999). In other example, Narumi et al. (Narumi et al., 2011) implemented a system that displays different scents to create the illusion of gustatory sensation and flavours in augmented reality (AR).

Olfactory interfaces are covering many other application scenarios such as desktop messaging notification (Maggioni et al., 2018), videogames (Mochizuki et al., 2004; Nakamoto et al., 2008), rehabilitation (Covarrubias et al., 2015), multimedia (Brewster et al., 2006; Matsukura et al., 2013) and communication (Ranasinghe et al., 2011; Zhang & Cheok, 2016). However, scent delivery is often considered challenging, and therefore several prototypes and techniques have been proposed. (Nakaizumi et al., 2006) and (Yanagida et al., 2004) proposed a scent projector consisting of vortex rings launched from an air cannon. In another example, SensaBubble (Seah et al., 2014) provides smell ambient notifications via bubbles containing scents, while Essence (Amores & Maes, 2017) provides a wearable option for scent delivery. Commercially available devices can also be found. Some examples are Vortex Activ USB, Scentee, oPhone DUO and Aroma Shooter (see Dmitrenko et al., 2016 for a comparison).

In the next chapters, we start our exploration of agency implication in novel user interfaces through a series of studies. We start by investigating agency experience in mid-air interfaces in Chapter 3. Beyond typical interaction techniques based on touch (e.g., keyboards and touchscreens), touchless systems are becoming increasingly popular. Many commercial devices (e.g., Leap Motion and Kinect) are being employed in applications ranging from entertainment to surgery. However, the role of the SoA in these systems has been unexplored, and the two studies in the following chapter address that lack.

Chapter 3
Agency in Mid-air Haptic Interfaces

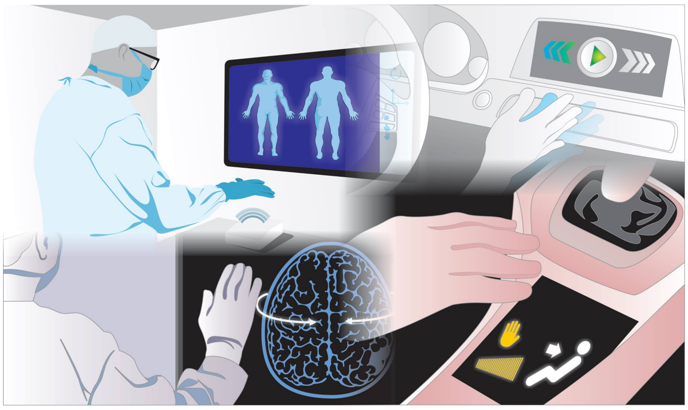


Figure 3.1 A mosaic of touchless interactions in surgery and driving scenarios.

Recent advances in gesture recognition technologies (Buckwald & David Holz, 2010; Lien et al., 2016) are driving a new class of interactive systems whereby a user is able to view, control and manipulate digital content without touching the interface. For example, touchless interactions are being explored as part of medical surgery (O'Hara et al., 2014), in the design of games that benefit children with autism spectrum disorder (ASD) (Bartoli et al., 2014), and touchless controllers for car dashboards (Asley, 2014) (see Figure 3.1). There is a strong user appetite for such systems as they are natural, having greater degrees of freedom for user movements.

One aspect of touchless interaction that has not been studied is the sense of agency (SoA). For example, in touchless application scenarios in which perceiving a responsive system is relevant (e.g., surgery and driving), if users do not experience perception of causation (a causal relationship between action and outcome), they could diminish self-attribution of an unfavourable outcome. However, although this perception is independent of correct performance of the device or system (i.e., personal agency), we can explore different interaction paradigms that enhance user's SoA in order to design more responsive touchless systems.

In physical interaction (e.g., keyboards and touchscreens) control can clearly be perceived as it involves touching objects. However, in mid-air interaction, where the main interplay involves gestures, agency could be challenging. To understand users' SoA when interacting with touchless interfaces, we conducted two user studies employing the intentional binding (IB) paradigm (Haggard et al., 2002). In the first study, we compared a camera-based button-click gesture with a physical button press, using both visual and auditory feedback. Our results show that both physical and gestural input modalities produced a binding effect only when the input action was accompanied by an auditory outcome and not by a visual outcome. In the second study, we compared the camera-based click gesture both with and without tactile stimuli (vibrotactile and mid-air) to examine if haptic feedback can enhance SoA. Our results show that haptic feedback produced higher IB than visual feedback only.

3.1 Touchless Button Click

To investigate the relationship between in-air gesture input and the system's responses, we measured IB during simple micro-interactions typical of desktop computing environments. We based our selection gesture on Saffer's statement, "The best, most natural designs, then, are those that match the behaviour of the system to the gesture humans might actually do to enable that behaviour. Simple examples include pushing a button to turn something on or off" (Saffer, 2008). Consequently, we chose a fundamental gesture action (touchless button click) and compared it with typical touch input (physical button press).

In this context, a button press movement is common in our everyday interaction with computers and smartphones. Besides, it can be reliably tracked with devices such as Leap Motion, which is specifically focused on hand and finger tracking. In common desktop computing environments, a physical button press generally produces three kinds of effect: (1) visual on-screen: when we press a button or key of the keyboard we normally expect a visual change on screen (e.g., typing tasks); (2) auditory feedback: because we can perceive a click sound through mechanical pressure on the actuator; and (3) haptic: because of the obvious physical contact with the mechanoreceptors of the skin. Therefore, we provided participants with visual, auditory and haptic feedback as the outcome of our physical and gestural action inputs to examine how states of input (physical and touchless) map onto states of the system.

3.2 Investigating Agency in Touchless Interfaces

3.2.1 Method and Materials

Participants judged their perception of time by reporting the position of a rotating dot around a Libet clock at the moment they either executed an action (baseline action and active action blocks) or received the feedback (baseline outcome and active outcome blocks), as shown in Figure 2.3. The numbers of the clock were not used to avoid creating visual patterns during the task.

The rationale behind this decision lies in two main aspects. First, the traditional Libet clock layout usually involves numbers on its perimeter (e.g., marks around the circle and numbers from 0 to 60 at intervals of five “clock-seconds” (Pockett & Miller, 2007)), and in pilot testing we noticed that, even when participants were instructed not to use the numbers on the clock face to determine their action, they tended to identify a number as a reference (e.g., “I’m going to do the action when the dot reaches the number 3”). However, we considered this does not reflect the volition/urge to execute the action.

Second, we wanted to explore a higher resolution of judgements, avoiding fixed ticks. That is, having discrete and fixed markers around the clock (e.g., 5, 10, 15, 20, etc.) constrains the granularity of time, being integer numbers mainly reported by participants. Therefore, to increase resolution and avoid creating visual patterns, we decided not to use the numbers, supporting our decision on previous studies that did the same (Demanet et al., 2013; Lynn et al., 2014; De Pirro et al., 2019) without a negative effect on the results.

Instead of verbally reporting the dot position using an integer number as a reference, participants used an external circular controller (Griffin Powermate USB Controller) to relocate the dot on the perceived position (with a resolution of around 7ms per step). This was similar to the study by (Pockett & Miller, 2007) in which participants were asked to mouse-click on the circle at the reported position. However, in our study, participants rotated the USB controller to move the dot around the clock, this being more natural.

The Libet clock was 500 pixels in diameter and was placed at the centre of a screen (24-inch, 1920 x 1080 resolution). Participants were asked to perform the action (either gestural or physical) whenever they felt the urge to do so. The perceived and actual times were recorded to calculate IB. In the trials with user-performed action, the action was either a touchless click gesture or a physical button press. The outcome was presented through one of four different feedback methods: on-screen visual, auditory (a beep), wearable vibrotactile, and mid-air haptic feedback.

3.2.1.1 Gesture Action

Participants moved their index finger, mimicking a button-press action (i.e., up–down finger movement of 2cm). The gesture was captured using a Leap Motion controller with capture rates of about 300 fps (Buckwald & David Holz, 2010). Participants rested their hand (palm down) at a fixed position of about 20cm above the surface of the Leap Motion device in all feedback conditions preceding a gesture action. Then, after a period of 250ms, a sensory outcome was given to participants.

3.2.1.2 Auditory Outcome

Auditory stimulus is a common sensory effect used in the IB paradigm. We considered audio feedback to have baseline comparison with new outcome modalities. In the conditions with auditory feedback, participants heard a tone that lasted 200ms at 900Hz using headphones. However, they always wore headphones during the full study.

3.2.1.3 Visual Outcome

Visual feedback was in the form of an on-screen button (250 pixels in diameter) that was presented at the centre of the screen and inside the Libet clock. When participants performed the click gesture, they could see an animation of this button changing state (the button sank as if it had been pressed; changed from red to green; and returned to its original state after 200ms). The procedure for presenting visual stimuli and the Libet clock is similar to those in previous studies (Moretto et al., 2011; McEneaney, 2013). Possible time delays due to the refresh rate of the screen used in our study (60Hz) in the visual conditions on screen, including the rotation of the Libet clock, was also compensated for by following the procedure of previous studies (Stewart, 2006). We executed a preliminary test with a photodetector and a high-speed camera placed in the middle of the screen to count the number of frames shown within specific periods of time. This was done to identify and compensate for missing frames. Our system was consistent in missing one frame in each trial, so to correct this delay, we subtracted the duration of one tick (16.66ms) from our interval durations, as in (Garaizar et al., 2014).

3.2.1.4 Vibrotactile Haptic Outcome

Vibrotactile feedback was given to participants using a wearable glove with an embedded coin vibration motor (model 310-103 by Precision Microdrives), 1cm in diameter and positioned in the glove so that the vibration is provided on the participant's fingertip (index finger). This motor vibrated at a speed of 12,000 rpm and 250Hz in frequency. The typical rise time of 87ms was compensated for to make timing as accurate as possible. Each vibration lasted 200ms, which was easily recognizable over the tactile channel (Gescheider et al., 2010). Participants did not wear the glove during visual, auditory and mid-air haptic feedback blocks.

3.2.1.5 Mid-air Haptic Outcome

Mid-air haptic feedback was provided using the UltraHaptics kit (Carter et al., 2013). This device uses low-intensity and low-frequency ultrasound pressure waves to create multiple focal points in mid-air for tactile sensations. The user can perceive the focal points using bare hands due to the mechanoreceptors in the skin evoking a haptic sensation. To equalize our two haptic feedback conditions in terms of the stimulation area, we simulated vibrotactile outcome features with an UltraHaptics kit. Five focal points were created on the tip of participants' index finger to cover an area of 1cm^2 with the same frequency as the vibrotactile condition (250Hz). The stimulation lasted for 200ms.

Figure 3.2 Experimental setup.

3.3 Study 1 – Touchless Vs Physical Action

Following RQ1 - Is a SoA experienced in touchless interaction? In this experiment, we compared traditional physical-based input with gestural-based touchless input. Both actions were accompanied by auditory and visual outcomes, in order to explore RQ2 - What type of feedback produces greater SoA in mid-air interfaces? This resulted in four combinations of action + outcome: physical & auditory, physical & visual, gestural & auditory and gestural & visual, as shown in Figure 3.3.

3.3.1 Procedure

Participants were asked to sit in front of a screen at a distance of about 100 cm. Every trial started when they pressed a footswitch to indicate they were ready to start. After this, a Libet clock was presented at the centre of a screen. The dot always started rotating from a random position. After one full revolution of the dot, participants were asked to perform the action: a physical button press using a keyboard (space key) or a click gesture in mid-air. For touchless action, the hand always stayed palm down and rested on top of a supporting structure (shown in Figure 3.2). For physical action, this structure was not used and the Leap Motion device was replaced by a computer keyboard. Participants always executed the action (gestural and physical) using their dominant hand.

After a period of 250ms, the outcome was presented in the form of auditory (a beep) and visual feedback on screen. Then, participants judged their perception of time by reporting the position of the dot on the clock. Participants wore noise-cancelling headphones to eliminate any audible noise from the devices. They performed 20 trials in each condition, resulting in 320 trials per participant (20 trials x 4 IB blocks x 4 combinations of action + feedback). The experiment was completed in a maximum time of 90min; there was a short break between conditions. Figure 3.3 shows the procedure of a single trial.

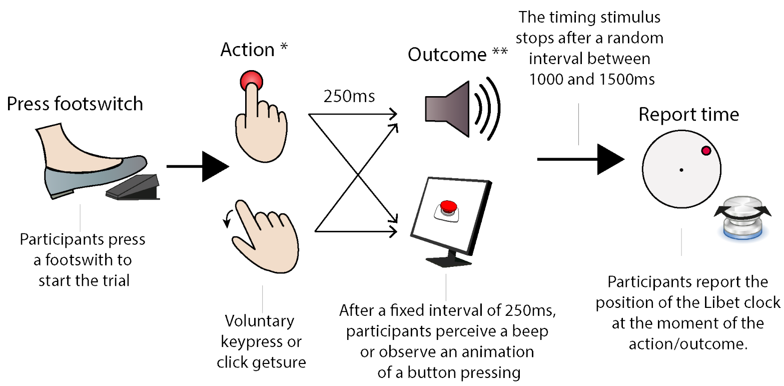


Figure 3.3 Experimental trial of Study 1. (*not done in baseline outcome blocks, ** not done in baseline action blocks).

3.3.2 Participants

Twelve right-handed participants (Four male, mean age=30.92 years old, SD=3.03) took part in the experiment. They had normal or corrected-to-normal vision. The local ethics committee approved this study and participants were not paid for their participation.

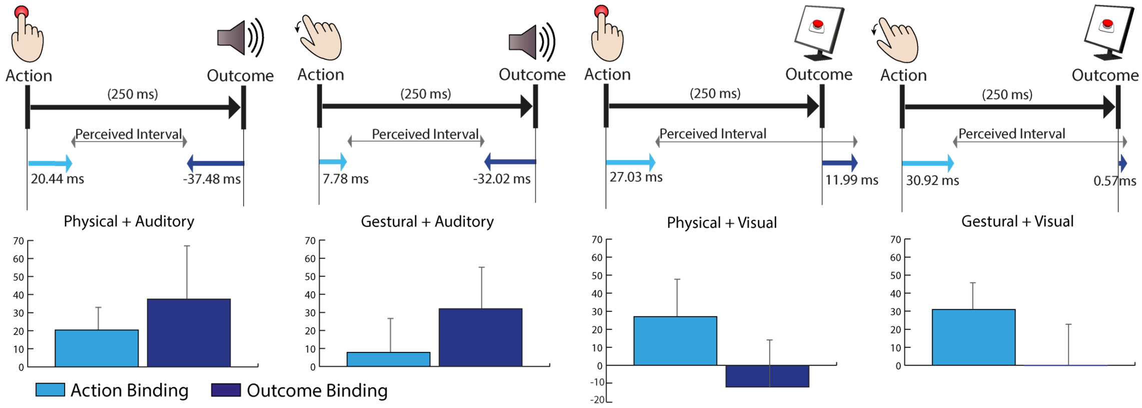


Figure 3.4 Average of action and outcome binding in milliseconds of each action and outcome modality. The sign of outcome binding on the chart bars has been inverted to allow for comparison with action binding. Error bars represent standard error of mean.

Action + Feedback	Action Binding	Outcome Binding	Total Binding
Physical + Auditory	20.44 ms (43.79 ms)	-37.48ms (106.23 ms)	57.92 ms (103.88 ms)
Physical + Visual	27.03 ms (73.50 ms)	11.99 ms (92.28 ms)	15.04 ms (109.42 ms)
Gestural + Auditory	7.78 ms (66.81 ms)	-32.02 ms (81.73 ms)	39.80 ms (106.01 ms)
Gestural + Visual	30.92 ms (52.76 ms)	0.57 ms (81.25 ms)	30.87 ms (68.30 ms)

Table 3.1 Average of action, outcome and total binding in milliseconds (with standard deviation in brackets) grouped by combination of action & outcome.

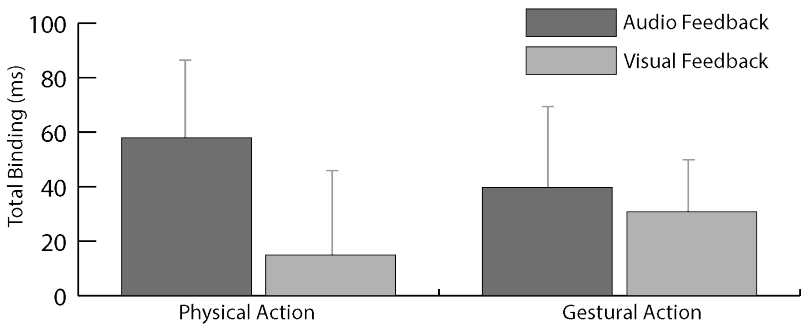


Figure 3.5 Average of total binding in milliseconds for each combination of action and outcome. Error bars represent standard error of mean.

3.3.3 Results of Study 1

Before comparing our main conditions, we first explored whether a binding effect was observed in the input modalities independently. To do so, we conducted repeated measures ANOVA tests to determine interactions between the baseline block (when only one event occurs, either action or outcome) and the active block (when both events occur – action and outcome) for both action binding and outcome binding (see Figure 2.3 for detailed blocks) in each input condition. We report the partial eta squared (η_p^2) as a measure of effect size according to (Cohen, 1977).

For the physical action a significant binding effect was always found between active and baseline blocks. Interestingly, a significant binding effect was also observed for the combination 'gestural action-visual feedback' ($F_{(1, 230)}$=15.28, p<0.001, η_p^2=0.062) only for the action binding but no such significant binding was observed for the outcome binding ($F_{(1,231)}$=0.008, p=0.929, η_p^2=0.013). Controversially, a significant binding effect was found for the combination 'gestural action-auditory feedback' for the outcome binding ($F_{(1,229)}$=9.16, p=0.003, η_p^2=0.038).

These results show a significant temporal binding effect for gestural action when accompanied by auditory feedback but not by visual feedback. Next, we present the comparison between the different types of action and feedback.

A repeated measure design was used to compare the effects of touchless input modality with physical-based input and visual and auditory feedback.

A 2X2 within subjects' ANOVA, with the type of action (touchless gesture-based click vs physical button press) and the type of feedback (visual vs auditory) as factors, revealed no significant effect of type of action on total binding ($F_{(1,11)}$=0.003, p=0.96, η_p^2=0.00). We also found no significant interaction between the type of action and type of feedback ($F_{(1,11)}$=0.63, p=0.45, η_p^2=0.05). However, there was a significant main effect for the type of feedback ($F_{(1,11)}$=5.31, p=0.04, η_p^2=0.33), with the auditory feedback scoring higher compared to the visual feedback. Figure 3.5 shows the average total binding with different action and feedback modalities.

An identical ANOVA was then performed for the action binding, showing no significant interaction ($F_{(1,11)}$=0.36, p=0.56, η_p^2=0.03) and no main effect for the type of action ($F_{(1,11)}$=0.12, p=0.74, η_p^2=0.01) and the type of feedback ($F_{(1,11)}$=0.79, p=0.39, η_p^2=0.07).

The outcome binding, however, showed a significant main effect for the type of feedback ($F_{(1,11)}$=9.17, p=0.01, η_p^2=0.45), with auditory outcome producing an increased binding in both the physical button press (M=-37.48ms, SD=106.23ms) and the touchless gesture-based click (M=-32.02ms, SD=81.73ms) compared to visual feedback respectively in the physical action (M=11.99ms, SD=92.28ms) and the touchless gesture-based click (M=0.57ms, SD=81.25ms). A breakdown of these means in relation to action and outcome binding is shown in Table 3.1. Figure 3.4 shows action binding and outcome binding effects.

3.3.4 Discussion of Study 1

Our results from Study 1 reveal an IB effect when both input modalities – gestural and physical – preceded auditory feedback. However, this effect was not observed with visual feedback. As shown in Figure 3.4, the visual outcome did not shift towards the action. This suggests that the touchless system exhibited significantly more IB when the input action was accompanied by auditory outcome compared with visual outcome. As expected, the physical button press preceding an auditory outcome produced IB, as previously shown in a large number of studies on SoA.

Interestingly, we found no statistically significant difference in the action binding across the different combinations of action and outcome. This could suggest that participants may have perceived the touchless action to be as responsive as the physical action in terms of IB, even when the touchless action did not involve typical characteristics of touching an object (e.g., proprioceptive perception). Proprioceptive perception plays an important role in terms of feeling immediate haptic feedback (as in pressing a physical button). In the study by (Coyle et al., 2012), participants reported increased IB for skin-based input modality, as this action involves tactile sensation in both the finger and the arm. Thereby, this seems a challenge for touchless action where implicit tactile feedback does not occur.

Although in our touchless condition there was not simultaneous action–feedback, like in the physical button press, interestingly we still found an IB effect, as the touchless action execution always involved participants' motor movement following a prior intention. Previous studies have suggested that the SoA principally arises due to internal motor signals (Blakemore et al., 2002; Moore & Haggard, 2008) and also that intention to act influences action attribution, when reafferent signals (e.g., motor or visual) match with intention retrospectively (Wenke et al., 2010; Chambon & Haggard, 2012, 2013). Thereby, ideomotor signals produced by the touchless action could have served as a contributory factor in our results on IB.

Furthermore, we also attribute these findings to the influence of the postdictive model of the origination of agency. As we state, “it is not necessary to physically touch an object to have the perception of a “button press” if it is associated with an effect in response (see Chapter 2 – Section 2.6.1). Although the touchless action did not involve immediate tactile feedback, participants always received a confirmation with a visual or auditory outcome. Similar accounts were reported in (Wegner et al., 2004; Banakou & Slater, 2014; Kokkinara et al., 2016), where subjects reported feelings of agency even when there was just the effect itself and no cause preceding the effect. Yet, in our studies, participants always had an intention to act and thereby a motor movement preceding an outcome. This could have contributed to the IB effect shown in our results.

3.4 Study 2 – Touchless Action: Visual Vs Haptic Outcome

To expand our RQ2 - What type of feedback produces greater SoA in mid-air interfaces? This experiment aimed to investigate if haptic feedback can improve participants’ SoA in gesture-based touchless interaction. For this, we measured IB both with and without haptic feedback.

3.4.1 Procedure

Participants in Study 2 used the same experimental procedure used in Study 1, with one exception. Whereas participants in Study 1 performed two kinds of actions (physical and touchless) and received two kinds of feedback (auditory and visual), in the second study participants performed only the touchless-based action and received visual, vibrotactile and mid-air haptic feedback (Figure 3.6). Both kinds of haptic feedback were provided on participants’ dominant hand (index finger). Participants wore noise-cancelling headphones to eliminate any audible noise from the devices. They performed 30 trials for each condition, resulting in 360 trials per participant (30 trials x four intentional binding blocks x three combinations of action + feedback). The experiment was completed in a maximum time of 90min; there was a short break between conditions. Figure 3.6 shows the procedure of a single trial.

3.4.2 Participants

Twelve right-handed participants (four females, mean age=30.33 years, *SD*=3.86), took part in the experiment. They had normal or corrected-to-normal vision. The local ethics committee approved this study, and participants were not paid for their participation.

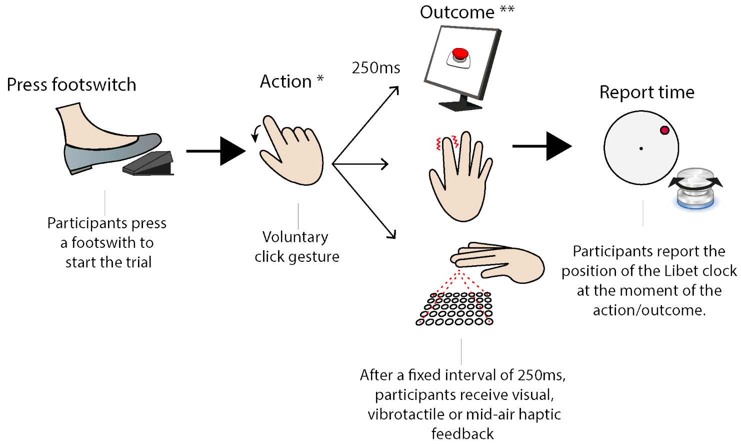


Figure 3.6 Experimental trial of Study 2 (*not done in baseline outcome blocks, ** not done in baseline action blocks).

3.4.3 Results of Study 2

A one-way repeated measure ANOVA was conducted to compare the effect of the three type of feedback (visual vs vibrotactile vs mid-air haptic) on the action, outcome and total binding. The results show a significant effect on the total binding ($F_{(2,22)}$=4.96, *p*=0.02, η_p^2=0.31) depending on the type of feedback. Post-hoc comparisons using Bonferroni correction showed that there is a statistically significant difference in the total binding specifically in the mid-air haptic feedback (*M*=84.21ms, *SD*=111.35ms) compared to the visual (*M*=-6.41ms, *SD*=82.98ms, *p*=0.02); but no such difference was found compared to the vibrotactile condition (*M*=40.77ms, *SD*=89.84ms, *p*=0.69). The difference between the visual and vibrotactile conditions was also not significant, *p*=0.23. Figure 3.8 shows the average total binding with different action and feedback modalities.

We found that the action binding was not significantly affected by the type of feedback ($F_{(2,22)}$=0.27, *p*=0.76, η_p^2=0.02). However, crucially, the outcome binding showed a significant difference ($F_{(2,22)}$=0.6.74, *p*=0.005, η_p^2=0.38). Post-hoc comparisons using Bonferroni correction showed that the outcome binding was significantly greater in the mid-air haptic condition (*M*=-64.79ms, *SD*=79.58ms) compared to the visual condition (*M*=12.68ms, *SD*=66.07ms, *p*=0.02), but there was no statistically significant difference between the mid-air haptic and the vibrotactile feedback (*M*=-29.13ms, *SD*=69.75ms,

p=0.69ms). Additionally, we found no significant difference between the vibrotactile and the visual condition, p=0.23.

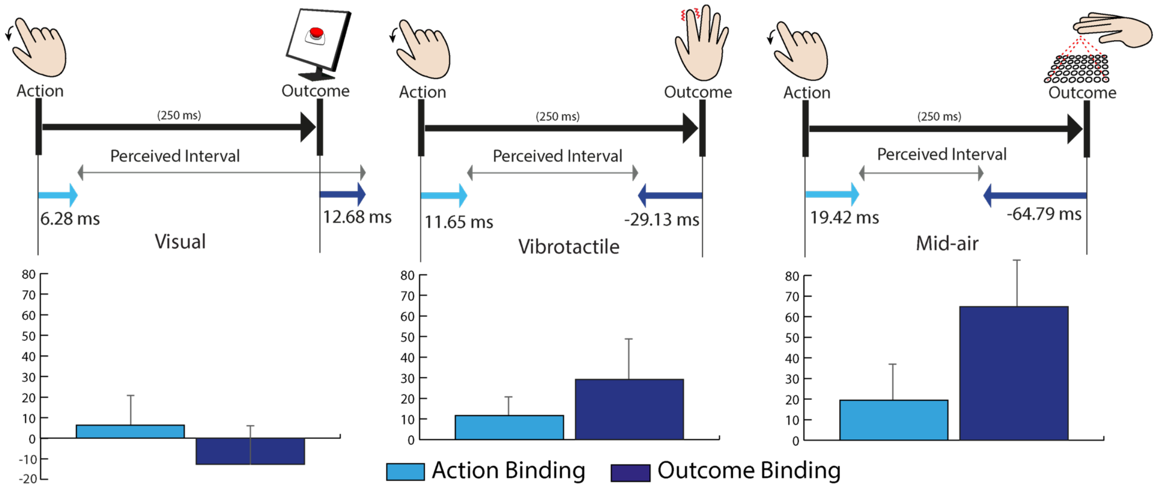


Figure 3.7 Average of action binding and outcome binding in milliseconds for each feedback type (visual, vibrotactile and mid-air). The sign of outcome binding effects on the chart bars has been inverted to allow for comparison with action binding. Error bars represent standard error of mean.

Feedback	Action Binding	Outcome Binding	Total Binding
Visual	6.28 ms (49.55 ms)	12.68 ms (66.07 ms)	-6.41 ms (82.98 ms)
Vibrotactile	11.65 ms (32.39 ms)	-29.13 ms (69.76 ms)	40.77 ms (89.84 ms)
Mid-air	19.42 ms (62.22 ms)	-64.79 ms (79.58 ms)	84.21 ms (111.35 ms)

Table 3.2 Average of action, outcome and total binding (with standard deviation in brackets) grouped by feedback type.

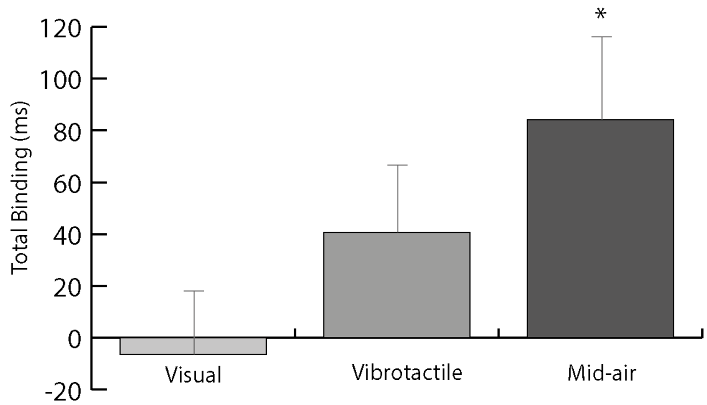


Figure 3.8 Average of total binding in milliseconds for each feedback type (visual, vibrotactile and mid-air). Error bars represent standard error of mean.

These findings suggest that mid-air haptic feedback produces the strongest effect in the IB values, and specifically in the outcome binding, compared to the other modalities. A breakdown of means in relation to action and outcome binding is shown in Table 3.2. Figure 3.7 shows action binding and outcome binding effects.

We performed further analysis using an independent sample t-test to compare the effect of the IB with auditory feedback in the touchless modality in Study 1 with the mid-air haptic feedback in Study 2. The results show no significant difference on the total binding ($t(22)=0.99$, $p=0.33$) between the auditory condition of Study 1 ($M=39.80$ms, $SD=106.02$ms) and the mid-air haptic condition ($M=84.21$ms, $SD=111.35$ms) of Study 2. These results were also not significant for the outcome binding ($t(22)=0.68$, $p=0.32$) in the auditory condition ($M=-32.02$ms, $SD=81.73$ms) compared to the mid-air haptic condition ($M=-64.79$ms, $SD=79.58$ms).

3.4.4 Discussion of Study 2

Our results from the Study 2 revealed an IB effect when the touchless input modality preceded a haptic feedback. However, this effect was not observed with visual feedback similar to Study 1. This suggests that the touchless system exhibited significant higher IB when participants received a haptic confirmation rather than a visual confirmation. Crucially, we found no statistically significant difference in action binding values across the outcome modalities.

Both haptic feedback conditions (vibrotactile and mid-air) shifted towards the touchless action. Interestingly, we found no statistically significant difference for outcome binding between these two haptic conditions. We set both outcome conditions with the same characteristics as much as possible. This is because vibrotactile feedback is higher in intensity compared with ultrasound. However, by creating five focal points of ultrasound overlapping each other to cover the same area as the vibrotactile stimuli, we could equalize between these two conditions.

3.5 General Discussion

Our results revealed the existence of IB effect in touchless gesture-based interactive applications. From our two studies, we found that gesture-based system exhibited significant higher IB when the input action was accompanied by haptic or auditory outcomes compared with visual outcome. Our results from Study 1 show an action binding effect in both physical and touchless interactions with no statistically significant difference, possibly suggesting that that our click gesture input could be perceived as responsive as the physical action in terms of IB, even when no simultaneous action-feedback occurred like in physical touch events. We attribute this result to ideomotor signals and the postdictive influence of agency in the IB paradigm, in which participants always receive an action confirmation with a visual, auditory or haptic outcome (in contrast to Coyle's work, in which only audio feedback was considered). Although we obtained different IB values from the tasks involving gesture input and visual feedback in both studies, we found no statistically significant difference in this condition between Studies 1 and 2.

Our results from both studies show different outcome binding effects depending on the type of feedback, with audio and haptic feedback producing higher IB effect than visual feedback only. Visual feedback on screen produced the lowest IB effect in both studies. This suggests that participants had a higher perception of controlling the touchless interface when they received an auditory or haptic confirmation rather than a visual confirmation. In cognitive neuroscience, a wide range of studies have employed audio feedback for studying agency, showing it to be a suitable modality to measure and produce SoA (Moore et al., 2009; Aarts et al., 2012; Moore & Obhi, 2012; Khalighinejad & Haggard, 2015). However, in our Study 2, we also found an IB effect with vibrotactile and mid-air haptic outcomes, with no statistically significant difference between them. This suggests that if one cannot provide audio feedback it may be preferred from an IB perspective to provide haptic feedback over visual-only feedback.

It is worth mentioning that we are aware the UltraHaptics device produces sound because of the ultrasound waves emission. In the frequency at which it works, audible sound is generated from its speakers. To address this, participants were asked to wear noise-cancelling headphones, not only during this condition but also for the entire task (including all the conditions).

3.6 Limitations

For the present work, we only explored implicit agency. We employed the IB paradigm as an implicit measure of the SoA, following evidence suggesting that increased IB is related to a higher experience of agency (Ebert & Wegner, 2010; Moore & Haggard, 2010). Since previous studies have suggested that self-reports of agency and IB may operate differently (Obhi & Hall, 2011), further research is needed to investigate the relation between explicit judgement of agency and IB for touchless interfaces. Additionally, in this work we put more attention on the impact of output modalities on agency, and further studies are needed to examine the effect of proprioceptive perception on the SoA in mid-air interactions, possibly by using the haptic devices to create more natural perception of touching real objects. Furthermore, we mainly compared visual feedback with the other modalities in our two studies, but a more direct comparison between audio and haptic feedback will be explored in future work.

This study involved a low sample of participants (N=12), being a first step to explore implicit agency in touchless systems. This could be considered a limitation and further studies with a bigger sample of participants are necessary to explore in more depth implicit agency in mid-air interactions.

Finally, the visual outcome employed in this study (an animation of a button being pressed) is very similar to the action itself; in other words, the outcome might be seen as a visual representation of the action, which can be considered a limitation. However, we chose such a visual outcome to explore agency in an ecological way. That is, when people use touchless systems, visual feedback usually constitutes the confirmation of the action. Because in gestural input, actions are so natural (e.g., pinch gesture to pinch an object, slide gesture to slide an object), visual feedback is usually presented as a visual representation of the action (Xuan et al., 2019). For this reason, in our study we employed an animation that confirms the action input (a button press), aiming to explore agency using a setup as similar as possible to a real application. Moreover, additional studies are needed to explore differences between "natural" visual outcomes that represent actions themselves and more "contrasting" visual outcomes that are not related with the action itself (e.g., a red flash on screen).

3.7 Conclusion and Application Scenarios

In this work, we have shown types of interaction that significantly impact users' SoA in order to provide solutions to improve touchless interfaces. Our results suggest that audio and haptic feedback better produce users' SoA compared with visual feedback. Although these kinds of feedback have been frequently used in past work (as mentioned in Chapter 2 – Touchless Systems), the role of SoA has been unexplored. Here, we have validated these feedback types through implicit metrics supporting their use to provide a better and more responsive interaction. Next, we explain some possible application scenarios.

Interactions in VR commonly rely on touchless actions; however, these systems often add haptic feedback, as they try to simulate real-world settings in order to provide a realistic interaction. We have demonstrated that touch and touchless input modalities accompanied by mid-air haptic feedback improve IB, which enables application scenarios for VR and bare-hands interactions. For example, by considering the role of agency in designing VR training simulators (e.g., flight or surgery), designers can approximate agency effects in users that are similar to those in a real-life situation. In this way, their commitment to the interaction (action inputs and system responses) might be stronger, enabling better training for the professional.

It is known that audio and haptic feedback releases the visual channel, allowing it to focus on additional tasks; this interplay is suitable for driving scenarios. Our results show that audio and mid-air haptic feedback improve users' SoA. This suggests that these kinds of feedback will not only help focus driving attention but also provide users with the feeling of being in control during touchless interactions (e.g., controllers for car dashboards). Additionally, mid-air haptic feedback represents a good means for private communication in cases where audio cannot be played, allowing the user to still experience agency.

Our results are in line with prior research suggesting that differences in interaction techniques can significantly affect the experience of control (Limerick et al., 2015). Inspired by these findings, and following the line of mid-air interfaces, in the next chapter we explore agency in olfactory interfaces. Beyond traditional interaction modalities based on vision, audio and touch, olfactory interfaces are becoming increasingly popular. Yet, as it is a modality newly introduced to user interfaces (e.g., in-car applications and VR), it is not clear how olfactory cues can influence our SoA. We therefore explore this aspect in Chapter 4 by modulating emotions though affective odours, following research which suggests that agency is modulated by emotional signals.

Chapter 4

Effect of Olfaction-mediated Emotions on the Sense of Agency

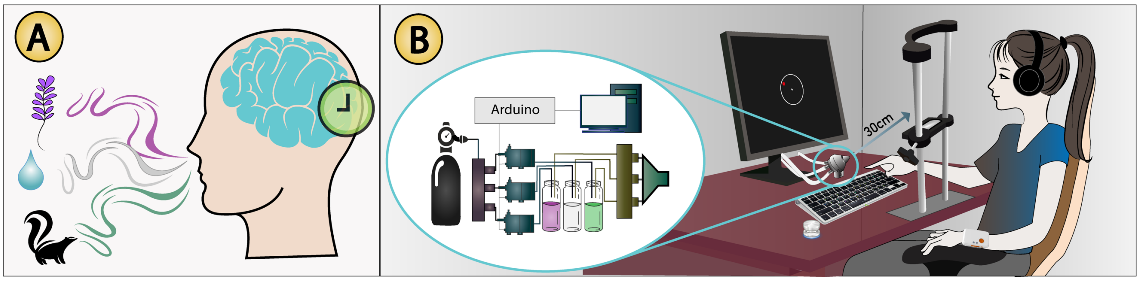


Figure 4.1 Scent priming approach. Participants were primed with positive (lavender), negative (civet) and neutral (water) scents to explore the effect of smell-induced emotions on intentional binding (IB) – the perceived temporal attraction between actions and outcomes. (B) Structure of the scent delivery system and setup for the IB task.

Olfactory interfaces are becoming increasingly popular as they provide compelling user experiences. However, our sense of smell is often considered poor compared with other senses (Shepherd, 2004), and thus our interaction with technology is dominated by visual, auditory and, more recently, haptic interfaces (Obrist et al., 2017). Nonetheless, olfaction is deeply connected to our mood (Warrenburg, 2005), memories (Herz & Cupchik, 1995) and emotions (Soudry et al., 2011), suggesting a strong potential to improve human-computer interaction (HCI) (Obrist et al., 2014). One unexplored aspect of olfactory interfaces is the effect of olfaction-mediated emotions on the Sense of Agency (SoA). As detailed in Chapter 2 - Section 2.8, agency studies have modulated the valence of emotions (positive and negative) using visual (Aarts et al., 2012), auditory (Yoshie & Haggard, 2013; Christensen et al., 2016) and somatosensory (Beck et al., 2017; Borhani et al., 2017) cues, and the role of olfactory information (i.e., emotions induced by odours) in agency has not been explored to date. With the increasing research on olfactory interfaces (Dmitrenko et al., 2017) (e.g., car scenarios (Dmitrenko et al., 2016) and virtual reality (VR) (Ramic-Brkic & Chalmers, 2014)) in the pursuit of providing multisensory experiences in HCI (Kortum, 2008; Obrist et al., 2017; Obrist et al., 2017), it is important to explore if olfaction-mediated signals affect the experience of agency.

Additionally, it is unclear if the modulation of agency is due to pure emotion activation to other parameters that in conjunction activate an emotion. That is, when triggering emotions through visual, auditory or somatosensory channels, there is an indirect path between the affective signal and the emotional area of the brain. For example, visual information coming from the eyes passes by the thalamus (responsible also for motor signals) and then reaches the visual cortex (Usrey & Alitto, 2015), where the valence of the content is evaluated. In contrast, olfactory signals directly trigger the amygdala (the area of the brain that controls our emotions (Zald & Pardo, 1997)) in an unmediated path (Aggleton & Mishkin, 1986). Therefore, if the SoA is modulated by affective odours, then we could conclude that agency is modulated by the effect of the emotions exclusively, instead of by other related processes.

To explore this, in this chapter we investigate the effect of emotions induced by olfactory information on the SoA using the intentional binding (IB) paradigm and found that IB increased when participants were exposed to a positive scent compared with negative and neutral scents. These findings indicate that olfactory information not only produces physiological responses (Vernet-Maury et al., 1999) and modifies emotions (Warrenburg, 2005; Soudry et al., 2011) but also affects the feeling of controlling the environment. We discuss the impact of our results in olfactory interfaces and HCI scenarios where the sense of smell can enhance user experiences.

4.1 User Study – Exploring the Effect of Odours on Agency

In this experiment, we primed participants with three different types of emotion (positive, negative and neutral) at the beginning of an IB task, as in the work by (Aarts et al., 2012). Participants were presented with two essential natural fragrances (lavender and civet oils) for positive and negative association, respectively, and one baseline scent (water) for neutral emotion (see Figure 4.1). In order to explore the effect of olfaction-mediated emotions on the SoA, and to answer both RQ3 - Do emotions produced by odours modulate the SoA? and RQ4 – Does a positive smell increase the SoA? we measured three main variables: (1) IB as an indicator of the SoA, (2) subjective emotion using a self-assessment manikin (SAM) scale to test whether the scents produced the intended emotion in participants and

(3) skin resistance as a measure of the physiological activation of the neural central system due to scent stimulation. Next, we present details of the procedures, methods and apparatus used in this study.

4.1.1 Intentional Binding Task Procedure

Every trial started when participants pressed a footswitch and a fixation cross was shown on screen while the scent was being presented (positive, negative or neutral) for 2500ms. After the scent presentation, a Libet clock was shown (with a rotating dot) which always started rotating from a random position. Then, participants were asked to freely press a button (space bar on a keyboard) at the elapsed time of their preference (i.e., voluntary action). After a fixed interval of 250ms, they perceived a tone (i.e., the action's outcome) which lasted 100ms at 900Hz in frequency. Subsequently, after a random interval between 1000ms and 1500ms, the clock stopped and participants were asked to report the position of the clock (where the dot was) at the moment when they either executed the action (baseline action and active action blocks) or perceived the tone (baseline outcome and active outcome blocks), as shown in Figure 2.3. The procedure of a single trial is shown in Figure 4.2.

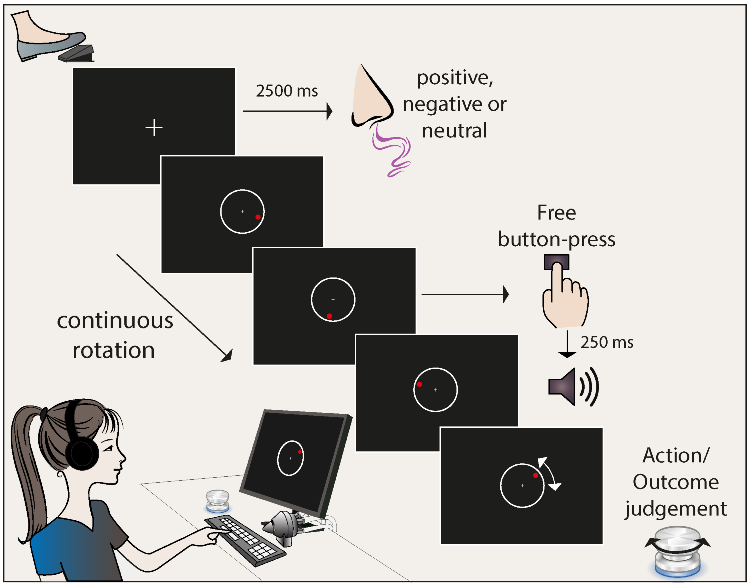


Figure 4.2 Procedure of the IB task. In baseline outcome blocks the action does not occur.

Between scent conditions, we used an air extractor in the room for about 3min to clear the environment. Participants performed four blocks (shown in Figure 2.3) of 20 trials each in each scent condition (three types), resulting in 240 trials per participant. Participants wore noise-cancelling headphones playing white noise during the entire experiment to block out sounds from the devices. The full experiment took about 90 min with a 3min break between conditions (air cleaning).

Participants were asked to remember the position of a rotating dot around a Libet clock (size 500 pixels) shown on screen (24-inch, 1920 x 1200 resolution) at the moment of their action/outcome. The clock rotated clockwise once every 2560ms. The numbers of the clock were not used to avoid creating visual patterns during the task. Instead, after each trial and when the dot stopped, participants used an external controller (Griffin Powermate Knob Controller) to relocate the dot on the perceived position. We then calculated the time errors by the difference between perceived and actual clock positions.

4.1.2 Scent Delivery

Figure 4.3 shows the structure of the delivery system. It consists of a custom-made electronic device controlled by an Arduino board. The device is composed of three electro-valves (4mm Solenoid/Spring pneumatic valve) that regulate the air passage (on–off) from a tank of compressed air. The tank (70l/s, maximum pressure of 8 Bar) supplied air flow through 4mm plastic pipes, passing through the electro-valves and entering three small glass bottles that contained two commercially available natural essential oils (lavender and civet) and water, respectively. The tank airflow was set at a constant pressure of 1 Bar-l/min, through an air regulator. This device was built following the guidelines from (Dmitrenko et al., 2017).

The odours reached the participant through a 3D-printed nozzle (diameter 3.5cm). The nozzle was positioned at about 30cm in distance from the participants' nose (Dmitrenko et al., 2017), and never directly in contact with the participant to avoid an air puff sensation. With our setup (see Figure 4.4), the scent takes about 1.5 seconds to be perceived by participants (from the valve triggers to participant judgement), as revealed in a pilot study we conducted before the actual IB experiment.

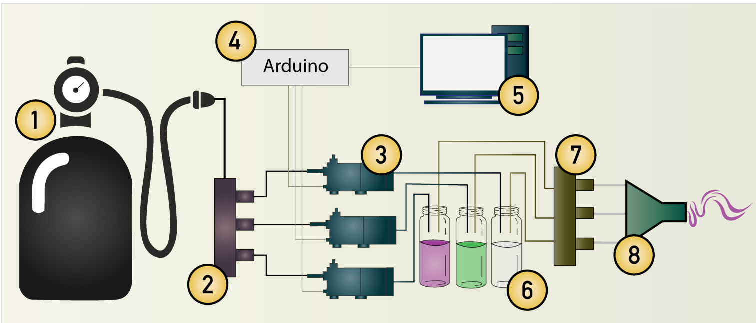


Figure 4.3 Structure of the scent delivery system: (1) air tank, (2) manifolds, (3) electric valves, (4) Arduino, (5) PC, (6) scents, (7) one-way valves, (8) output nozzle.

During the entire experiment, participants rested their chin on a supporting structure critically positioned to ensure scent delivery to the participants' nose. Figure S1 shows the real setup. The fragrances used were 100% pure, undiluted essential oils. Civet oil is often used as a perfume base. However, in its pure state it is considered unpleasant since it is the perineal gland secretion produced by the civet cat (Sbrollini, 1987; Johansen, 2008). Civet oil is commercially available on the (Plush Folly) website and lavender oil on the (Barrett and Holland) website.

We are aware of cultural variability in odour perception and so chose civet as our negative scent since it has been effectively used for inducing negative emotions (Zarzo, 2008; Rinaldi et al., 2018) and been categorized as unpleasant by study participants in different cultures: French, Vietnamese, American (Chrea et al., 2004), Swiss, British, and Singaporean (Ferdenzi et al., 2013), showing no significant differences between gender.

4.1.3 Subjective Emotional Assessment

To evaluate whether the scents produced the desired emotion in participants, we employed a SAM scale (Bradley & Lang, 1994) after each scent condition to obtain the three dimensions of emotion (valence, arousal and dominance) from participants. A 9-point rating scale was employed for each dimension. A value of 9 represents a high rating in each dimension while a value of 1 represents a low rating in each dimension. The SAM scale has been extensively used in previous studies to evaluate emotions induced by exposure to odours (Bestgen et al., 2015) as it uses graphical representations of the three dimensions of emotion (using manikins), providing an intuitive scale for subjects. Additionally, the SAM scale has been used to obtain large amounts of emotional data for multisensory stimulation studies (Gatti et al., 2018). The SAM scale is shown in Appendix 1.

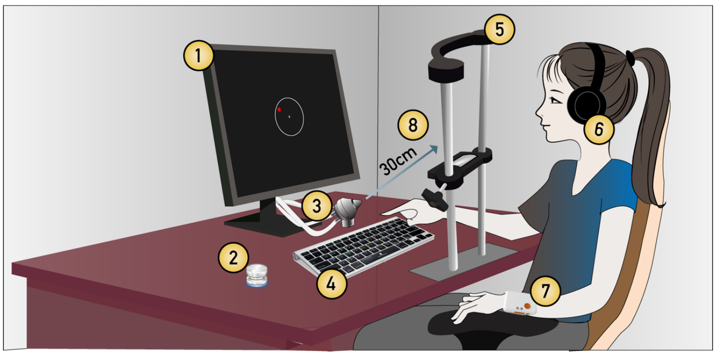


Figure 4.4 Experimental setup. (1) Libet clock on screen, (2) USB controller, (3) output nozzle, (4) keyboard, (5) chinrest, (6) headphones, (7) skin resistance sensor, (8) Distance – 30cm.

4.1.4 Skin Resistance Assessment

Previous studies have shown that physiological signals such as skin resistance can be modulated by the perception of odorants (Van Toller et al., 1983; Vernet-Maury et al., 1999; Bensafi et al., 2002; Gatti et al., 2018), which is a product of neural central system activation. To explore whether such activation occurs with the scents used in our study, we measured skin resistance with and without scent stimulation. Skin resistance was measured using a Shimmer3 GSR+ Unit wireless device (Shimmer Sensing, Dublin). Participants wore an armband with the shimmer device attached and two 8mm snap style finger electrodes on their index and middle fingertips (with a constant voltage 0.5V). We recorded data with a frequency of 512Hz (10 mSiemens (µS)/volt, A/D resolution of 12 bit) allowing us to record responses ranging from 2 to 100µS. We recorded skin resistance during the scent conditions, namely, neutral, positive and negative (see Figure 4.2) for 5s in each trial and also during a baseline condition consisting of 60s prior to the experiment, without exposure to any scent.

4.1.5 Participants

Thirteen right-handed participants (four females, mean age=31.39 years old, SD=5.33) took part in our study. They had normal or corrected-to-normal vision and were pre-screened prior to the experiment using an olfactory assessment test (shown in Appendix 1) to make sure their sense of smell was not impaired and that they were not suffering from allergies, cold or flu. Females during their menstrual cycle or pregnancy were excluded since hormone levels can change olfactory sensitivity. The local ethics committee approved this study.

An a priori statistical power analysis was performed for sample size estimation in G*Power. Running a power analysis on a repeated measures ANOVA with three emotional scent conditions (i.e., neutral, positive, and negative, repeated four times corresponding to the four blocks of the IB paradigm), a power of 0.95, an alpha level of 0.05, and a medium effect size (f=0.25, η_p^2=0.06, critical F=1.63) (Faul et al., 2007; Lakens, 2013), requires a sample size of approximately 12 participants. Thus, our proposed sample of 13 participants was adequate for the main objective of this study.

4.2 Results on Emotions

A one-way repeated measures ANOVA for each dimension of emotions (i.e., valence, arousal and dominance) was conducted to compare the effect of the emotional scents on participants' judgement. Partial eta squared (η_{p^2}) is reported as a measure of effect size according to Cohen (Cohen, 1988).

	Valence	Arousal	Dominance
Positive	6.08 (1.89)	3.85 (2.15)	5.46 (1.66)
Neutral	5.08 (1.25)	2.84 (1.77)	5.15 (1.90)
Negative	4.23 (1.83)	3.84 (1.40)	5.0 (1.73)

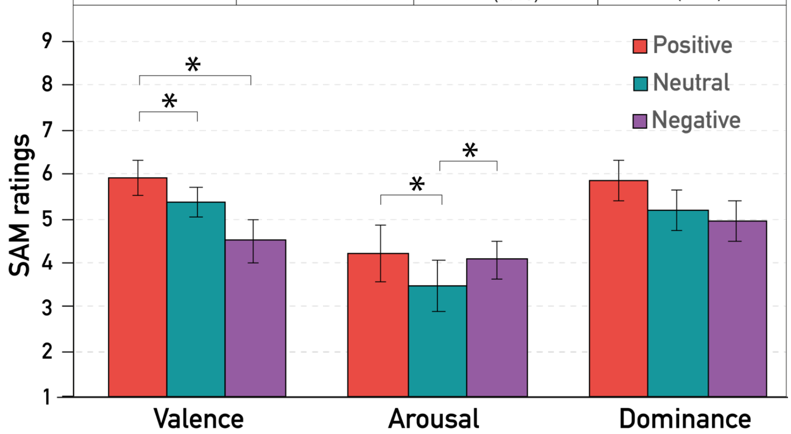


Figure 4.5 Results on emotions. Top: Average of the emotional responses from participants using the self-assessment manikin (SAM) scale (rated with a 9-point rating scale) grouped by smell type with ± SD in brackets. Bottom: Plot for comparison of the three emotional dimensions (pleasure, arousal and dominance) per smell type. Error bars represent SEM. * =*p*<0.05 in valence.

The results show a significant effect of scents on valence ($F_{(1,11)}$=4.65, p<0.05, η_p^2=0.28), and further comparison tests with Bonferroni correction showed a significant difference between all three scents (see Figure 4.5 for the mean scores). A significant effect on arousal was also shown ($F_{(1,11)}$=4.87, p<0.05, η_p^2=0.22), and further comparison tests with Bonferroni correction showed a significant difference between neutral and positive (p<0.05) and neutral and negative (p<0.05) scents. However, a non-significant effect of scents on dominance was shown ($F_{(1,11)}$=0.144, p=0.71, η_p^2=0.01).

4.3 Results on Intentional Binding

Before comparing our three main conditions (positive, negative and neutral), we first explored whether a binding effect was observed in each scent condition independently. To do so, we conducted repeated measures ANOVA tests to determine interactions between the baseline block (when only one event occurs, either action or outcome) and the active block (when both events occur – action and outcome) for both action binding and outcome binding (see Figure 2.3 for detailed blocks) in each scent condition.

For the positive scent, we found a significant binding effect between the baseline (M=-1.86ms, SD=129.5ms) and active (M=29.18ms, SD=102.86ms) blocks for the action condition ($F_{(1,270)}$=15.473, p<0.001, η_p^2=0.054). Similarly, we found a significant binding effect between baseline (M=109.29ms, SD=123.35ms) and active (M=61.75ms, SD=112.130ms) blocks for the outcome condition ($F_{(1,264)}$=32.08, p<0.001, η_p^2=0.108).

For the neutral scent, a significant binding effect was found between the baseline (M=5.33ms, SD=103.32ms) and active (M=27.55ms, SD=105.42ms) blocks for the action condition ($F_{(1,266)}$=6.82, p=0.01, η_p^2=0.025). Meanwhile, a significant binding effect was found between the baseline (M=99.48ms, SD=116.6ms) and active (M=75.14ms, SD=135.02ms) blocks for the outcome condition ($F_{(1,265)}$=6.43, p=0.012, η_p^2=0.024).

Finally, for the negative scent we found a significant binding effect in the action condition ($F_{(1,265)}$=4.624, p<0.032, η_p^2=0.017) between the baseline (M= -6.05ms, SD=19.21ms) and active (M=18.1ms, SD=97.52ms) blocks. Controversially, for the outcome condition, we found a non-significant binding effect ($F_{(1,266)}$=1.149, p=0.285, η_p^2=0.004) when comparing the baseline (M=90.58ms, SD=114.58ms) and active (M=79.74ms, SD=129.83ms) blocks.

These results show a significant temporal binding effect in each timing technique independently. Next, we present the comparison between the three timing techniques

A one-way repeated measures ANOVA was conducted to compare the effect of the scents used as an emotional prime (i.e., neutral, positive, and negative) on action, outcome, and total binding. The results show a significant effect of the emotional prime on the total binding ($F_{(1,11)}$=4.50, p<0.05, η_p^2=0.26). Particularly, comparison tests with Bonferroni correction showed a significant difference between the neutral and positive emotional scents (p<0.01) and between the positive and negative (p<0.05) scents. The results also show a significant effect of the emotional scent on the outcome binding ($F_{(1,11)}$=5.53, p<0.05, η_p^2=0.30), while comparison tests with Bonferroni correction showed a significant difference between the neutral and positive (p<0.01) and the positive and negative emotional scents (p<0.05). However, for action binding ($F_{(1,11)}$=1.08, p=0.05, η_p^2=0.16), we found no significant effect between the three scents. Details related to mean time of action, outcome and total binding in each of the emotional prime conditions are presented in Figure 4.6.

	Action Binding	Outcome Binding	Total Binding
Positive	25.60 ms (39.99 ms)	-44.95 ms (49.89 ms)	70.20 ms (56.69 ms)
Neutral	13.27 ms (19.90 ms)	-16.27 ms (55.20 ms)	23.70 ms (62.68 ms)
Negative	21.97 ms (22.98 ms)	-6.80 ms (90.42 ms)	19.22 ms (105.35 ms)

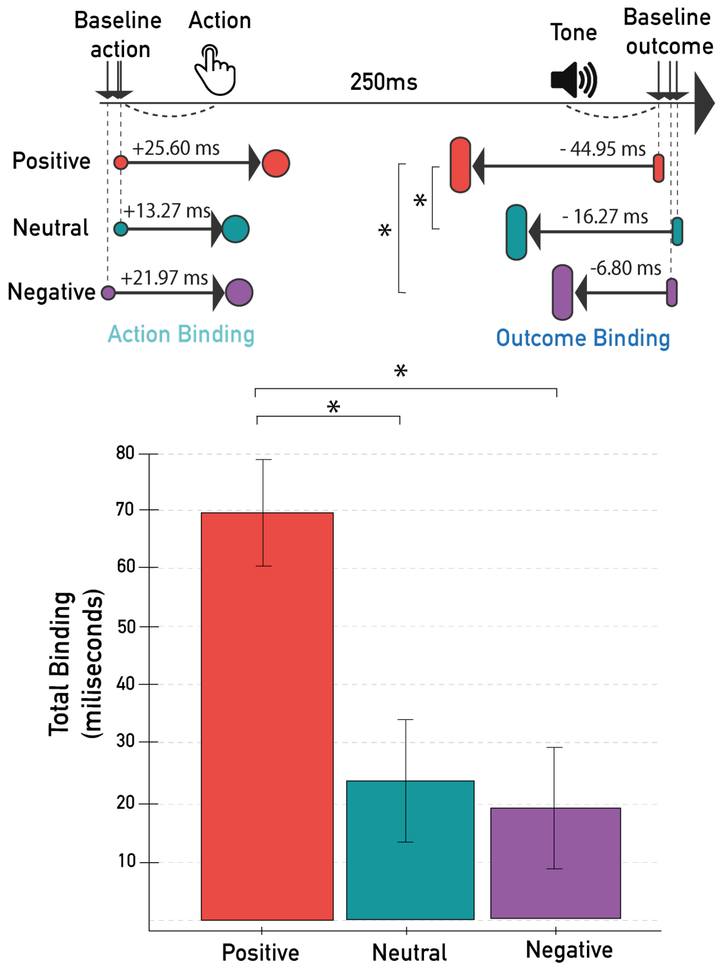


Figure 4.6 Results on intentional binding. Top: Average of action, outcome and total binding in milliseconds of each smell modality, with ± SD in brackets. Middle: Plot for comparison: a positive value represents a delayed awareness of the action (action binding) and a negative value an early awareness of the outcome (outcome binding). Bottom: Total binding (Action Binding – Outcome Binding). Error bars represent SEM. * = p<0.05.

4.4 Results on Skin Resistance

A one-way repeated measure ANOVA was conducted to compare the effect of the scent stimulation on skin resistance reactions. The results show a significant effect of scents on skin resistance ($F_{(1,11)}$=4.34, p<0.05, η_p^2=0.28). Particularly, comparison tests with Bonferroni correction show a significant difference between the baseline and all the scent conditions (p<0.01). However, no significant effect is shown between the three emotional scents (positive, negative and neutral). Figure 4.7 shows the mean skin resistance in ohms.

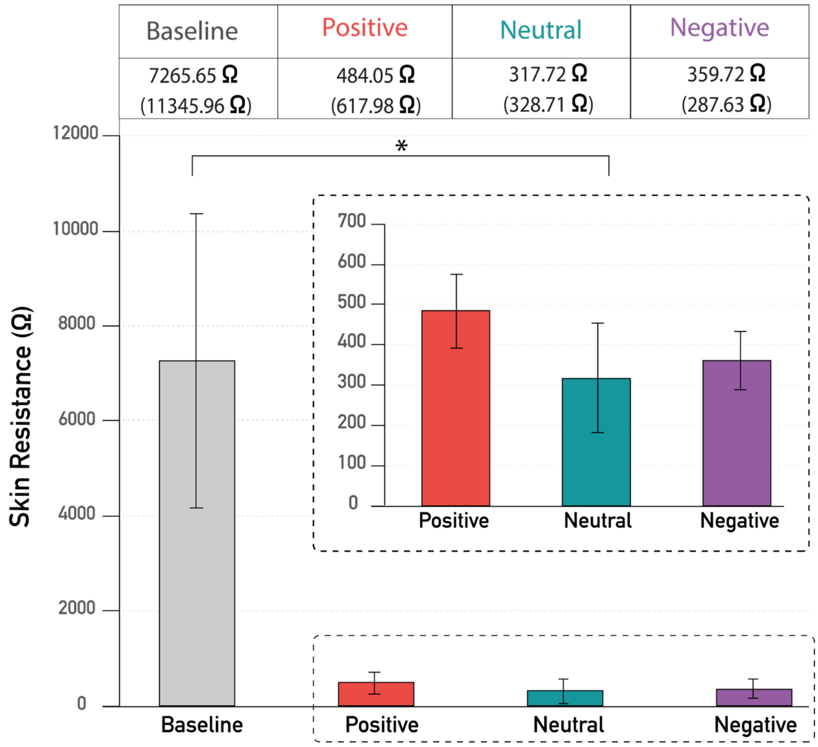


Figure 4.7 Results for skin resistance. Top: Average of galvanic skin response (resistance) collected from participants in ohms (Ω), with ±SD in brackets grouped by scent type and the baseline condition. Bottom: Plot for comparison: the upper dashed rectangle shows a zoom of the emotional scents: positive, neutral and negative. * =*p*<0.05.

4.5 Discussion

Our results show that the scents we employed in our study effectively produced the intended emotions on participants (positive, negative and neutral), as revealed in the analysis from the SAM scale. Participants scored the lavender scent significantly higher in valence compared with the civet and water scents, while the civet scent was reported with the lowest valence. While the mean scores of valence for the three scents sit around the middle of the SAM scale (see Figure 4.5) we found that the differences between scents were statistically significant in our analysis. Additionally, the mean score of valence for the scent of lavender (~6) is consistent with previous studies (Serrano et al., 2016; Brianza et al., 2019) as well as for the scent of civet (~4) (Rinaldi et al., 2018), which confirms the validity of our results.

In terms of arousal, the lavender scent was scored with low arousal (see Figure 4.5), which supports that lavender odour is relaxing (Motomura et al., 2001). However, the water scent was reported as significantly less arousing than the lavender and civet scents. Yet, further studies are needed to explore scents with high valence and high arousal. Finally, no effect on dominance was found.

The analysis of skin resistance shows a significant difference between the baseline condition (i.e., prior to the IB experiment without the exposure to scents) and the emotional scent conditions. In line with prior work, this suggests that participants' skin resistance was affected by the elicited emotion, which confirms that there was a response from the neural central system due to the scent stimulation (Hongratanaworakit, 2004; Weber & Heuberger, 2008). However, while we observed higher skin resistance for the positive scent (see Figure 4.7) we found no statistically significant difference between scents.

Crucially, we found that participants exhibited significantly higher total IB in the positive valence condition (Figure 4.6). This suggests that participants felt higher SoA when they were exposed to the lavender scent compared with the civet and water scents. These findings are in accordance with prior research on modulation of agency through emotional cues. That is, people tend to self-attribute events when positive information is involved, unlike negative information (the self-serving bias) (Babcock & Loewenstein, 1997). Although previous studies modulated the valence of emotions (positive, negative or neutral) using visual (pictures) (Aarts et al., 2012), auditory (e.g., human vocalizations) (Yoshie & Haggard, 2013; Christensen et al., 2016; Yoshie & Haggard, 2017) and even somatosensory (cutaneous heat-pain) (Beck et al., 2017; Borhani et al., 2017) cues, in the present study we show that the experience of agency is modulated by olfactory cues, these being higher when a positive scent is presented.

As shown in Figure 4.6, we found no differences in action binding (the delayed awareness of the action) between the different emotional conditions. However, we observed significantly higher outcome binding (the anticipated awareness of the outcome) with the positive scent in contrast with the neutral and negative scents (see Figure 4.6). This is in line with the work from Aarts and Haggard (Aarts et al., 2012; Beck et al., 2017), in which the main effect was observed on the outcome binding. This suggests that the positive reward signal through a pleasant scent caused a stronger prediction of the outcome.

Unlike other sensory modalities (e.g., vision, audio or touch), the sense of smell provides a direct path between olfactory information and the amygdala (Zald & Pardo, 1997), and clinical research indicates that "emotional behaviour is critically dependent on the amygdala" (Aggleton & Mishkin, 1986). Our results provide evidence of agency modulation via a channel that is directly connected to our emotions, suggesting that an increase in the SoA is unlikely to be produced by additional parameters that accompany other sensory modalities.

These results represent an opportunity to design user interfaces that improve user's SoA through multisensory signals. Although the sense of smell is often considered a primitive sense (Shepherd, 2004; Obrist et al., 2017), and its inclusion in HCI seems challenging (Ghinea & Ademoye, 2011) (especially in light of delivery issues (Dmitrenko et al., 2017)), in this study we have demonstrated that the feeling of controlling the environment increases when people are exposed to a pleasant scent.

4.6 Implications for HCI

Next, we present a number of HCI application scenarios employing olfactory interfaces to which our results can contribute.

4.6.1 In-vehicle Interfaces

Our results might explain why fragrance presentation is known to improve performance in driving scenarios (Baron & Kalsher, 1998). Our study suggests that presenting a pleasant scent (e.g., lavender), could help drivers to feel more in control during in-car interaction involving voluntary actions/commands (e.g., turn the steering wheel) and responses from the car (e.g., perceiving the car moving).

A smell notification system with varying scent presentation could not only modulate alertness and mood but also induce levels of agency, depending on driver requirements. For example, when drivers need to be awake, a peppermint scent (known to produce alertness (Yoshida et al., 2011)) can be emitted. Then, a positive scent such as lavender could be presented when drivers need more control and engagement (e.g., when approaching a curve which lacks lane markings). These variations in scent types will avoid the habituation issues common in olfactory interfaces (Dmitrenko et al., 2017).

Another example is autonomous driving. Studies have investigated how to effectively alert drivers during "autonomous mode" that a critical situation is approaching. When an "Emergency Automation Off" message is presented, drivers delay taking back control (Mok et al., 2017), and a quick response is needed to avoid an accident. Emergency notifications can be accompanied by scent presentation so that the car not only communicates a message but also helps drivers to take over agency in a critical situation.

Therefore, driving assisted by olfactory signals in an actual car environment will be investigated in future work to explore optimum performance while driving.

4.6.2 Virtual Reality

It has been demonstrated that VR "leads to bodily responses similar to those expected in a real-world analogue, such as increased heart rate and skin conductance, and decreased skin temperature" (Bohil et al., 2011). In our study we found that participants showed a change in skin resistance due to the smell stimulation (in line with prior work). A virtual environment accompanied by scent presentation can provide users with responses that enhance realism and the virtual experience, contributing thus not only to the sense of presence but also supporting experience of agency through emotional changes.

In future work, we will explore actual VR environments where scent presentation can modify levels of agency. For example, users could have a higher feeling of controlling a menu system while perceiving pleasant scents. On the other hand, there are situations in which users need to disconnect from an interaction. For example, VR has been used in post-traumatic stress disorder treatment (Maples-Keller et al., 2017), during which patients are exposed to virtual situations that may be disturbing (e.g., that induce fear or danger). Here, at specific points during the scene visualization, a negative scent can be presented so that the user loses self-attribution of the situation (e.g., a car accident). Reducing agency could help a patient to continue a task or session while feeling less connection with the moment ("it is not me who is doing this").

4.6.3 Sensory Substitution

Our findings might also contribute to research on deaf-blindness (people who only have the senses of touch, taste, and smell to interact with the outside world) and sensory substitution systems (Hamilton-Fletcher et al., 2016). These systems can convert visual information into another sensory modality (e.g., sound) (Chebat et al., 2018). For instance, visual characteristics (e.g., size, movements, colours, etc.) are mapped into sound patterns so that blind people can even hear a colour (Hamilton-Fletcher et al., 2016). However, for deaf-blind people this is more challenging, and the sense of smell could represent a medium to convey visual or other sensory information, for instance, smell colours. Our research opens opportunities to increase smell-based assistance to give deaf-blind persons another interaction channel that not only communicates information

(Li et al., 2017) but also provides a feeling of control and empowerment (Hamilton-Fletcher et al., 2016).

Unlike common sensory modalities employed in HCI (e.g., vision, audio and touch), the sense of smell is starting to be introduced in our interaction with technology. Our study aims to advance understanding of the role of olfaction on the SoA through affective information. With our study we aim to provide researchers with insights that may be useful when designing for olfactory interfaces that support an instinctive sense of control during interactions between humans and computers.

4.7 Limitations

We observed a low IB in the neutral condition. A possible reason for this low value suggests that presenting a "neutral scent" is challenging. Even when we used water instead of essential oils, and the elements (e.g., vales, manifolds bottles, etc.) were completely independent in each scent condition (see Figure 4.3), participants might have smelled components from the system. Indeed, two participants reported having perceived the neutral scent as a slightly plastic-like scent, which could be caused by the plastic tube used to transport the air or the 3D-printed nozzle. Although we expected to observe higher IB in the water condition, the main effect from the positive scent was clearly observed in comparison with the other two conditions (see Figure 4.6). However, further studies are needed to compare neutral conditions using odourless materials (e.g., glass tubes to transport the essential oils) in order to compare a more reliable neutral scent.

We expected to observe an effect of the scent conditions (positive, negative and neutral) on skin resistance (e.g., differences between pleasant and unpleasant scents) according to prior studies (Brauchli et al., 1995). One possible reason for the lack of significance could be the habituation effect typical in smell stimulation (Pellegrino et al., 2017). Studies have shown a significant decrease in odour pleasantness with time (when an odour was initially pleasant) after 20 repeated odour presentations (Ferdenzi et al., 2014). Additionally, (Croy et al., 2013) suggested that repeated presentation of an unpleasant scent reduces its salience. Our IB study took about 90min in total, including a 3min beak between conditions, which means that each scent condition took about 27min, including four blocks used in the Libet clock method (two baseline and two active blocks, as shown in Figure 2.3) repeated 20 times each. This resulted in 80 presentations of each scent. To the best of our knowledge, this is the first study using the IB paradigm while employing scent stimulation, and therefore further studies are needed to explore scent exposure while controlling the habituation effect, perhaps by conducting the task on different days or reducing the number of trials by using a different agency measure (e.g., the interval estimation method). Finally, our sample size (N=13) was low as this was a first step to explore the effect of olfaction-mediated emotions on the SoA. Therefore, further exploration is needed with a larger number of participants.

4.8 Conclusion

In this chapter, we investigated the effect of emotions evoked by affective odours on the SoA. Evidence that agency is modulated by emotions was previously revealed. However, to the best of our knowledge this is the first study that explored affective modulation of agency via emotional scents. Our results show that olfactory information not only modifies emotions and produce changes in physiological responses but also affects the feeling of controlling the environment. By using the IB paradigm, we found that the SoA increased when participants were exposed to a positive scent compared with a neutral or negative scent. We discussed how our findings can be exploited in relevant HCI applications, such as VR, in-car interaction or sensory substitution, and hence contribute to the creation of multisensory experiences that support a SoA.

Inspired by these results, in the next chapter we explore different sensory modalities to address common limitations of agency measures related to visual demand. Current visual timing methods to measure agency (e.g., the Libet clock) are limited in scenarios that involve relevant visual information (Coyle et al., 2012) (e.g., in VR), as they require subjects' attention to report spatial position. For instance, in Chapter 3, we found reduced SoA for visual feedback that was presented inside a Libet clock, and a method that does not require visual cues could have been more suitable for evaluating agency in visual tasks (e.g., involving visual feedback).

Since in Chapter 4, we found that a different sense (the sense of smell) beyond the typical senses involved in HCI (vision, audio and touch) could serve as a medium to convey information and produce an effect on agency, in Chapter 5, we explore whether different senses can be used to measure perception of time. We then present the development of two novel timing techniques based on auditory and haptic cues that provide a reference for reporting the time at which events occur (action/outcome), which can be employed in the IB paradigm.

Chapter 5

Modality Variants for Agency Measurements

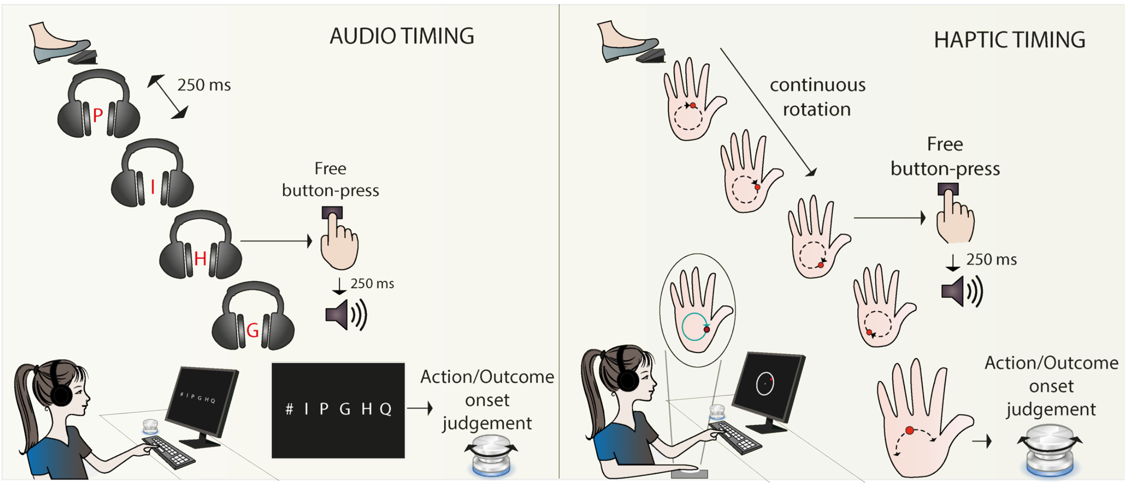


Figure 5.1 Audio timing (left) and haptic timing (right). Alternative cues to measure sense of agency using the intentional binding paradigm.

Due to the sense of agency (SoA) having mainly been explored in the fields of psychology and cognitive neuroscience, current agency measurements might be limited when used in human-computer interaction (HCI), particularly when involving visual demand (e.g., the Libet clock method). In this chapter, we describe two user studies that extend the intentional binding (IB) paradigm by exploring two variations of timing stimuli beyond the Libet clock. We aimed to expand implicit measures of the SoA for more interactive and visual tasks and therefore proposed an audio alphabet sequence and a haptic clock on the hand as timing stimuli to be used in the IB paradigm (Figure 5.1). We then compared them with two known timing methods based on visual cues: the traditional Libet clock and a visual alphabet on screen. We hypothesized that by changing the layout of the timing cue while keeping key features (e.g., speed, frequency), we could reduce the current limitations of conventional visual stimuli and still allow an IB effect to be observed. Additionally, we assessed user emotion by using our timing methods to evaluate user experience and engagement.

Our results demonstrate that *audio timing* through a voice sequence (audio alphabet) and *haptic timing* through rotating stimulation on the hand (haptic clock), measured an IB effect that was not statistically different from that measured with the Libet clock. This suggests our methods are suitable alternatives for measuring the SoA using the IB paradigm while addressing current limitations of the traditional method (e.g., visual demand and lack of engagement). We discuss how our work contributes to the emerging research of agency in HCI, aiming to advance understanding of agency in human interactions with technology.

5.1 Timing Stimuli Adaptations

The Libet clock's appearance and spatio-temporal properties are associated to a typical representation of time measure; aside from its speed, it has the same characteristics as a conventional clock, including rotatory cues and numeration. However, the key feature that provides its main function is its particular speed (which accommodates time differences in the hundreds of milliseconds). Nonetheless, previous work has adapted the Libet clock by removing the numbers (Demanet et al., 2013; Lynn et al., 2014) and providing visual cues inside it (Moretto et al., 2011; McEneaney, 2013), with no negative effect in the results.

Alexander et al. (Alexander et al., 2016) proposed a modified version of Libet's paradigm to study cognitive decision in contrast to motor decision. They added a stream of letters inside each quadrant of the clock, and participants were asked to choose a letter and indicate the clock position at the moment when the choice was made. Moreover, in past work, the timing stimuli was completely changed by using a letter stream on screen without the clock (Soon et al., 2008; Cavazzana et al., 2014; Cavazzana et al., 2017). In these cases, participants were asked to remember the letter that was shown at the moment when they felt the urge to act in a freely paced motor task (button press). This approach provides the advantage of showing an unpredictable sequence while avoiding common inaccuracies in rotating stimuli (Van De Grind, 2002). However, these adaptations remain within visual cues on screen.

As we wish to address common limitations of visual stimuli, in this chapter we propose a set of timing stimuli that employ auditory and tactile cues, thus releasing the visual channel and enabling visual attention towards other activities. In the next section, we describe two user studies that compared traditional visual timing methods with novel timing methods in an IB task in order to answer RQ5: Can the IB paradigm be employed using a non-visual timing stimulus? Additionally, in each study we conducted an evaluation on the dimension of emotion (valence arousal and dominance) in order to answer RQ6: Do non-visual timing stimuli reduce lack of engagement?

5.2 Study 1 – Exploring Auditory Timing

In our first study, we investigated the effect of auditory timing stimuli in an IB task. We compared *audio timing* through a voice sequence (audio alphabet), with two known visual timing methods: the traditional Libet clock and a stream of letters on screen (visual alphabet). We then measured IB to explore if a similar effect is observed in *audio timing* compared with visual timing.

5.2.1 Intentional Binding Task Procedure

Every trial started when participants pressed a footswitch that caused the timing stimulus to be presented. Then, they were asked to freely press a button (space bar from a keyboard) at the elapsed time of their preference (i.e., voluntary action). After an interval of 250ms, they heard a tone (i.e., the action's outcome) which lasted for 100ms at 900Hz. Subsequently, after a random interval between 1000ms and 1500ms, the timing stimulus stopped, and participants were asked to report the cue (visual or auditory) that was presented at the moment they either executed the action (baseline action and active action blocks) or perceived the tone (baseline outcome and active outcome blocks), as shown in Figure 2.3.

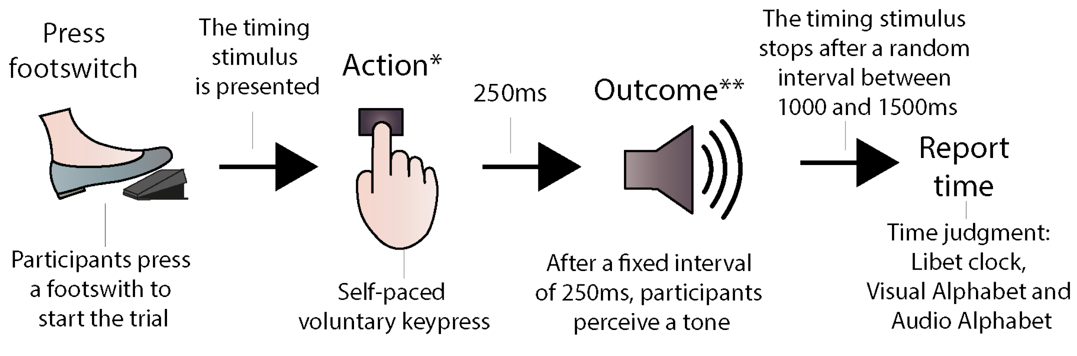


Figure 5.2 Intentional binding task procedure of Study 1 (*not done in baseline outcome blocks, ** not done in baseline action blocks).

Participants judged their perception of time using three timing methods (Libet clock, visual alphabet and audio alphabet). For each trial, the judgement error was calculated as the difference between the perceived and actual time. Following this, the IB between action and outcome was measured. Thus, a positive value represented a delayed awareness, while a negative value an early awareness. Participants performed four blocks (shown in Figure 2.3) of 30 trials each in each timing method (three types), resulting in 360 trials per participant. The full experiment took about 90min, with a 2min break between conditions. Figure 5.2 shows the procedure of a single trial.

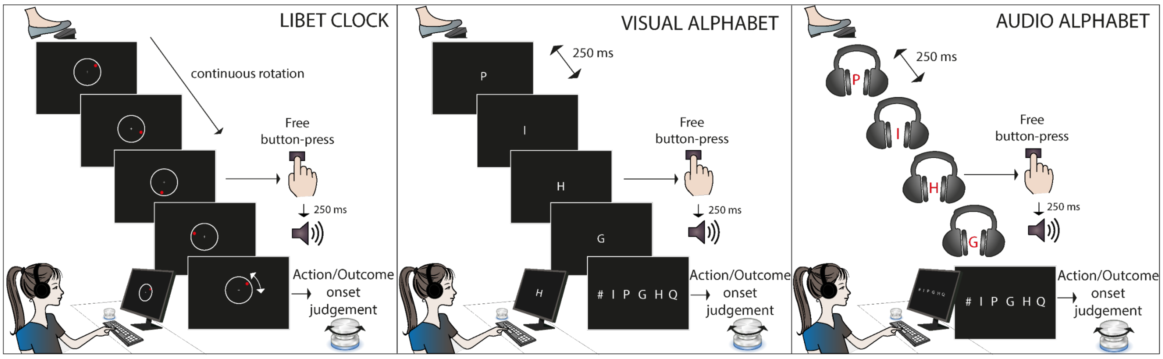


Figure 5.3 Experimental tasks of Study 1 for the three timing methods: Libet clock (left), visual alphabet (middle) and audio alphabet (right).

5.2.2 Libet Clock Method

In the Libet clock method (Figure 5.3 left), participants had to remember the position of a rotating dot around a Libet clock (size 500 pixels) shown on screen (24-inch, 1920 x 1080 resolution) at the moment of their action and outcome. The clock rotated clockwise once every 2560ms. The numbers of the clock were not used to avoid creating visual patterns during the task. Instead, after each trial, participants used an external controller (Griffin Powermate Knob Controller) to relocate the dot on the perceived position.

5.2.3 Visual Alphabet

The Visual Alphabet timing condition (Figure 5.3 middle), was similar to that used in prior work (Soon et al., 2008; Cavazzana et al., 2014; Cavazzana et al., 2017). Participants were presented with an unpredictable stream of consonants on screen; every consonant was presented for 250ms in a continuous sequence without any time interval between consonants. After each trial, participants were asked to report the letter shown on screen (24-inch, 1920 x 1080 resolution) at the moment of their action/outcome. They were shown a response mapping with five options corresponding to the letter shown during the actual action and outcome (0-back), two letters immediately before (1-back & 2-back) and two letters immediately after (1-forward & 2-forward) (Cavazzana et al., 2014; Cavazzana et al., 2017). An additional option was given (the # symbol) in case any of the letters shown corresponded to their answer, namely, the perceived time was greater than 2-back/2-forward. Figure S2 in Appendix 4 shows a comparison of the experimental setup for both the Libet clock condition and the Visual Alphabet condition.

5.2.4 Audio Alphabet

In the audio alphabet timing condition (Figure 5.3 right), the procedure was similar than the visual alphabet timing. However, it differed in that the sequence of consonants was presented in the form of a pre-recorded voice (250Hz in frequency) through headphones, with no visual cues. The frequency of the voice sequence (the same as in the visual alphabet condition) was determined in a pilot study to identify the speed at which the consonant being said was understandable. After each trial, participants were asked to report the letter they heard at the moment of their action\outcome using a response mapping on screen, as in the visual alphabet condition. Participants wore headphones during the entire experiment (including all the conditions).

5.2.5 Emotion Assessment

To explore how participants experienced our methods, after each condition they were asked to answer a questionnaire to evaluate their emotions by using the three timing methods. They were instructed to report their emotion in relation to the timing method they used. We employed a PAD scale (Mehrabian & Russell, 1974) composed of an 18 bipolar adjective pairs questionnaire (Agarwal & Meyer, 2009) to measure the three main dimensions of emotions (higher order factors): pleasure (valence), arousal and dominance (Russell & Mehrabian, 1977). These emotional dimensions provided an evaluation of the level of enjoyment, engagement and dominance that participants had during the study regarding the three timing methods. Particularly, the pleasure dimension provided insights about how enjoyable/annoying the task was, the arousal dimension helped to explore how engaged/bored participants felt during the task and finally the dominance dimension allowed exploring how dominant/dominated they felt during the task. This dimension is particularly relevant for agency studies since dominance is often related to how "in control" subjects feel (Fontaine et al., 2007).

We used this particular scale (e.g., rather than a self-assessment manikin (SAM) scale as in the previous chapter) because it provides a variety of adjectives (see Appendix 3). It decomposes the dimensions of emotion into 18 independent bipolar adjectives, giving broader insights into how participants experienced the task. For instance, it allowed us to identify whether participants reported being bored, relaxed, sleepy, stimulated, etc. Given that we wanted to explore whether our new techniques were more engaging than the Libet clock, we considered this scale as more suitable than a SAM scale. Additionally, since we collected only implicit data and not qualitative data (e.g., interviews or anecdotal experiences), we employed the adjectives of the PAD scale as a report from participants of how they experienced the new techniques.

5.2.6 Participants

Sixteen right-handed participants (five females, mean age=28.38 years old, SD=4.62) took part in the study. They had normal or corrected-to-normal vision. The local ethics committee approved this study, and participants were not paid for their participation. Two participants were excluded because of highly variable time judgement, leaving 14 participants for the analysis.

An a priori statistical power analysis was performed for sample size estimation in G*Power, using a repeated measures ANOVA with three timing methods (i.e., Libet clock, visual alphabet and audio alphabet, repeated four times corresponding to the four blocks of the IB paradigm). A power of 0.80, an alpha level of 0.05, and a medium effect size (f= 0.25, η_p^2= 0.06) (Faul et al., 2007; Lakens, 2013), requires a sample size of approximately 12 participants. Thus, our proposed sample of 14 participants was adequate for the main objective of this study.

The parameters used in our power analysis were similar to those reported in previous IB studies. For example, in the study by (Christensen et al., 2016), a sample size of 15 was suggested while in the study by (Christensen et al., 2019) a sample size of 20 was suggested.

5.2.7 Results on Intentional Binding

Before comparing our three main conditions (Libet clock, visual alphabet and audio alphabet), we first explored whether a binding effect was observed in each timing condition independently. To do so, we conducted repeated measures ANOVA tests to determine interactions between the baseline block (when only one event occurs, either action or outcome) and the active block (when both events occur – action and outcome) for both action binding and outcome binding (see Figure 2.3 for detailed blocks) in each timing condition. Partial eta squared (η_p^2) is reported as a measure of effect size according to (Cohen, 1977).

For the Libet clock method, we found a significant temporal binding effect between the baseline (M=57.48ms, SD=130.86ms) and active (M=110.63ms, SD=141.09ms) blocks for the action condition ($F_{(1,397)}$=35.369, p<0.001, η_p^2=0.032). Similarly, we observed a significant temporal binding effect between baseline (M=184.32ms, SD=164.66ms) and active (M=143.79ms, SD=230.44ms) blocks for the outcome condition ($F_{(1,396)}$=8.716, p =0.003, η_p^2=0.022).

In the case of visual alphabet, a significant binding effect was found between the baseline (M=57.48ms, SD=130.86ms) and active (M=110.63ms, SD=141.09ms) blocks for the action condition ($F_{(1,397)}$=35.369, p<0.001, η_p^2=0.082). Meanwhile, a significant binding effect was found between the baseline (M=119.85ms, SD=137.11ms) and active (M=98.69ms, SD=153.45ms) blocks for the outcome condition ($F_{(1,391)}$=4.604, p=0.033, η_p^2=0.012).

Finally, for audio alphabet we found a significant binding effect in the action condition ($F_{(1, 378)}$=14.338, p<0.001, η_p^2=0.037) between the baseline (M=-6.93ms, SD=199.34ms) and active (M=49.53ms, SD=220.3ms) blocks. Similarly, for the outcome condition, we found a significant binding effect ($F_{(1,375)}$=5.003, p=0.026, η_p^2=0.013) when comparing the baseline (M=8.41ms, SD=209.88ms) and active (M=-22.61ms, SD=211.96ms) blocks.

These results show a significant temporal binding effect in each timing technique independently. Next, we present the comparison between the three timing techniques.

A one-way repeated measures ANOVA for each of the binding measures (action, outcome and total binding) was conducted across the three timing methods (i.e., Libet clock, visual alphabet and audio alphabet).

The results show a non-significant effect of the timing methods on the total binding ($F_{(2, 26)}$= 0.271, p=0.76, η_p^2= .043), and similar results are shown for action binding ($F_{(2, 26)}$= 0.490, p=0.62, η_p^2= 0.13) and outcome binding ($F_{(2, 26)}$= 0.267, p= 0.77, η_p^2= 0.043). We found no significant difference on the binding effects (i.e., action, outcome and total binding) due to the timing methods used. Details related to mean scores in relation to action, outcome and total binding in each of the timing methods are shown in Figure 5.4.

	Action Binding	Outcome Binding	Total Binding
Libet Clock	29.81 ms (79.5 ms)	-41.79 ms (132.43 ms)	72.59 ms (153.85 ms)
Visual Alphabet	56.73 ms (75.5 ms)	-19.78 ms (100.01 ms)	76.5 ms (143.71ms)
Audio Alphabet	53.75 ms (91.48 ms)	-36.31 ms (57.24 ms)	90.06ms (89.72 ms)

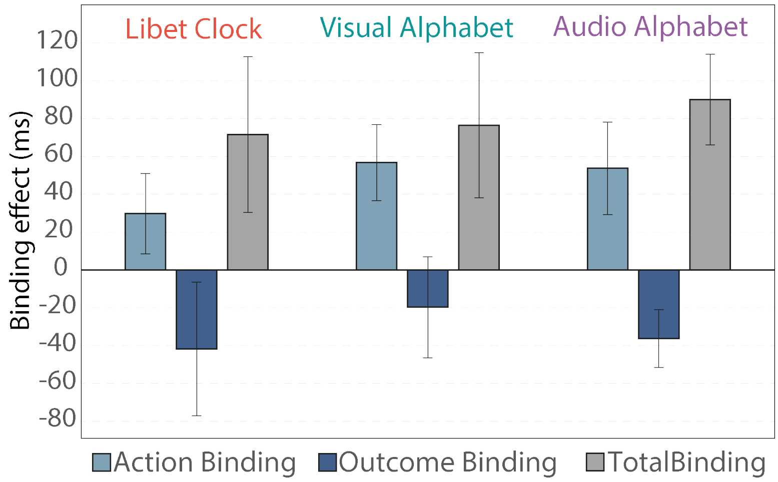


Figure 5.4 Results on intentional binding. Top: Average of action, outcome and total binding in milliseconds (with SD in brackets) grouped by timing method. Bottom: Plot for comparison; a positive value represents a delayed awareness while a negative value an early awareness. Total Binding = Action Binding – Outcome Binding. Error bars represent standard error of mean (SEM).

5.2.8 Results on Emotion

A factorial analysis (principal components analysis (PCA), applying a Varimax rotation with Kaiser normalization) was performed to obtain the three dimensions of emotion (pleasure, arousal and dominance) from our PAD scale (details are shown in Appendix 3, Table S1). Figure 5.5 shows the obtained values (normalized) for each dimension.

A one-way repeated measure ANOVA for each dimension of emotions (i.e., pleasure, arousal and dominance) was conducted to compare the effect of the three timing methods on participants' emotions. The results show a non-significant effect of timing methods on pleasure ($p>$ 0.5). Conversely, significant effects on dominance ($F_{(2, 26)}$= 8.31, p= 0.002, η_p^2= 0.54) and arousal ($F_{(2, 26)}$= 9.55 , p= 0.001 , η_p^2= 0.53) are shown. Post-hoc comparisons using Bonferroni correction show that there is a statistically significant difference in the dominance dimension between the Libet clock method (*M*= -0.58, *SD*= 1.06) and the visual alphabet (*M*= 0.12, *SD*= 1.12, *p*= 0.02) and audio alphabet (*M*=0.58, *SD*= 0.49, *p*= 0.01) methods. Post-hoc comparisons using Bonferroni correction also show that there is a statistically significant difference in the arousal dimension between the Libet clock method (*M*= -0.49, *SD*= 0.91) and the audio alphabet method (*M*= 0.63, *SD*= 0.81, *p*= 0.008), and between the visual alphabet (*M*= -0.13, *SD*= 0.84) and the audio alphabet (*p*= 0.02) methods.

5.2.9 Discussion of Study 1

Our results show that the IB effect measured with the two traditional methods (i.e., Libet clock and visual alphabet) in an IB task consisting of a button press action and tone outcome did not differ statistically from that measured with the audio alphabet. This suggests that participants' time judgement was not modified due to the timing method used (visual or auditory). The IB values found with the Libet clock and visual alphabet methods are in accordance with previous work (Cavazzana et al., 2014; Cavazzana et al., 2017), which confirms the validity of our studies.

By being visually demanding, visual methods are difficult to fit in interfaces and situations within HCI. For instance, studies on illusory agency using VR have been limited by explicit measures (i.e., questionnaires), which are subject to a number of cognitive biases (Wenke et al., 2010; Stenner et al., 2014).

	Pleasure	Arousal	Dominance
Libet Clock	0.54 (0.59)	0.25 (0.45)	0.21 (0.53)
Visual Alphabet	0.49 (0.34)	0.43 (0.42)	0.56 (0.56)
Audio Alphabet	0.53 (0.37)	0.81 (0.40)	0.79 (0.24)

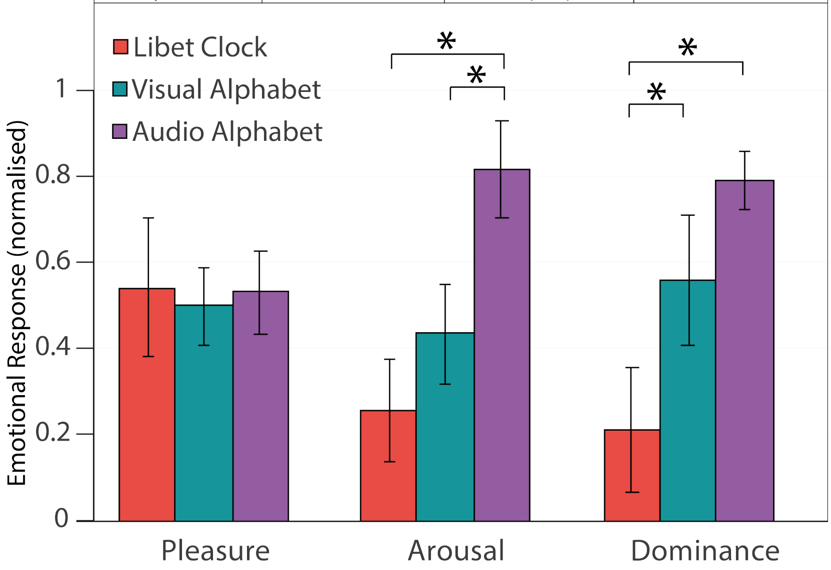


Figure 5.5 Results on emotions. Top: Average of the emotional responses from participants using the PAD scale grouped by timing method, with SD in brackets (values are normalized). Bottom: Plot for comparison of the three emotional dimensions (pleasure, arousal and dominance) per timing type. Error bars represent standard error of mean (SEM).

In this chapter, we hypothesized that an IB effect could also be observed using a timing stimulus that does not require relevant visual information in order to establish a move towards measuring agency in more interactive tasks. Our results provide insights about alternative solutions to employ the IB paradigm in VR applications.

By using auditory timing (i.e., an audio sequence), it could be possible to implicitly measure SoA in tasks involving active conditions, for instance, observation of an avatar motion (to evoke the feeling of body ownership) without full attention to a rotating dot. Additional audio sequences could be used (e.g., pitch or numbers), although this needs to be further investigated.

Although visual and auditory stimuli have been demonstrated to behave differently in terms of reaction time (Geffen et al., 1973), we found no statistically significant difference in terms of IB effect (i.e., the perceived time interval between a voluntary action and its sensory effect). This suggests that audio timing could be an alternative timing method when measuring SoA in the IB paradigm. For instance, a sequence of voice could be presented to users while manipulating an interface (e.g., menu navigation), thus directing the relevant visual attention towards other activities (e.g., observation of virtual hands on screen, moving and activating buttons).

The duration for which the letter was shown on screen in the visual alphabet condition was different compared with previous studies, in which the duration of the visual cue was set as 500ms (Soon et al., 2008) and 150ms (Cavazzana et al., 2014; Cavazzana et al., 2017). However, we set the duration for presenting the letters on the basis of a pilot study to identify the speed at which the consonant being said was understandable (i.e., 250ms). We then established the same frequency for the two timing methods involving the alphabets (visual and auditory) in order to fairly compare them. In the audio alphabet condition, participants visually chose the consonant on screen (using response mapping) for experimental reasons (Figure 5.3 right). However, this can be done verbally as well.

The analysis of emotional responses from participants shows non-significant differences between the three timing methods regarding the pleasure dimension. However, our results suggest that participants felt significantly more aroused and dominant when using *audio timing* compared with the Libet clock. The IB task usually requires a number of trial repetitions to compute the average of judgement error (usually 30 trials). This task may be tiring as it is repetitive, which can produce lack of engagement in participants. In our experiment, some of the participants reported that the Libet clock was "boring" and "hypnotizing", and at the end of the task they mentioned feeling "sleepy". Our results from the PAD scale reflect this experience, as participants reported being significantly more "awake" and "stimulated" while performing the task with the audio alphabet. This suggests that *audio timing* could better suit a more interactive task that requires more commitment (e.g., VR) while still being an applicable time measure in the IB paradigm.

5.3 Study 2 – Exploring Haptic Timing

In our second study, we introduced a *haptic timing* condition and compared it with visual timing using the typical Libet clock (see Figure 5.6). In contrast to visual cues to measure time perception, *haptic timing* has not been explored. *Haptic timing* allowed us to measure perception of time based on tactile cues, reducing the requirement of visual information. The Libet clock condition was identical to that described in the first study (Figure 5.7 left). In the *haptic timing* condition (Figure 5.7 right), the procedure was similar, but here the clock was presented in the form of a rotating haptic stimulation on participants' palm.

5.3.1 Intentional Binding Task Procedure

The procedure for the IB task was identical to that shown in the first study (see Figure 5.2). Participants heard white noise during the entire experiment to block sound from the devices used. Participants performed four blocks (shown in Figure 2.3) of 30 trials each in each timing method (two types), resulting in 240 trials per participant. The full experiment took about 45min with a 2min break between blocks. Figure 5.6 shows the procedure of a single trial, and Figure 5.9 shows the experimental setup.

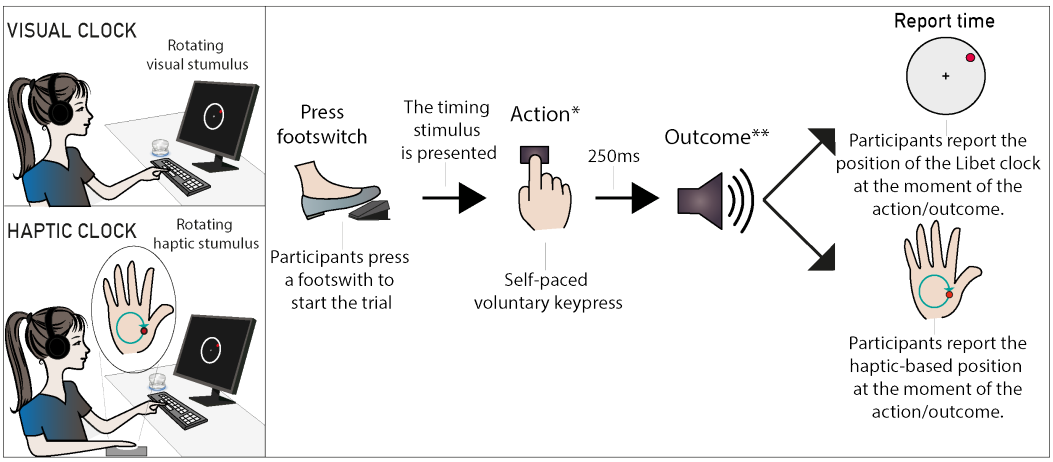


Figure 5.6 IB task procedure of Study 2 (*not done in baseline outcome blocks, ** not done in baseline action blocks).

5.3.2 Haptic Clock

Before the task started, participants were instructed to place their non-dominant hand (palm down) on a custom-made box (Figure 5.8) containing a brush attached to a NEMA-17 Bipolar 48mm Stepper (model 42BYGHW811). The stepper was controlled using an Arduino board and programmed to rotate clockwise at the same speed as the Libet clock (2560ms per revolution) with a resolution of 3.2ms/step (360°=800steps). The diameter of the rotational circumference was adjusted depending on hand size (normally smaller for female) but was about 6cm. Participants performed the action (button press) using their dominant hand, and the *haptic timing* stimulus was provided on the non-dominant hand. Finally, participants reported the position on the hand where they felt the tactile stimulus at the moment of the action/outcome using an external Griffin Powermate Knob Controller (as in Study 1) to physically relocate the position of the brush on the hand (Figure 5.7 right). Figure S3 and Figure S4 in Appendix 4 show additional pictures and screenshots of the setup.

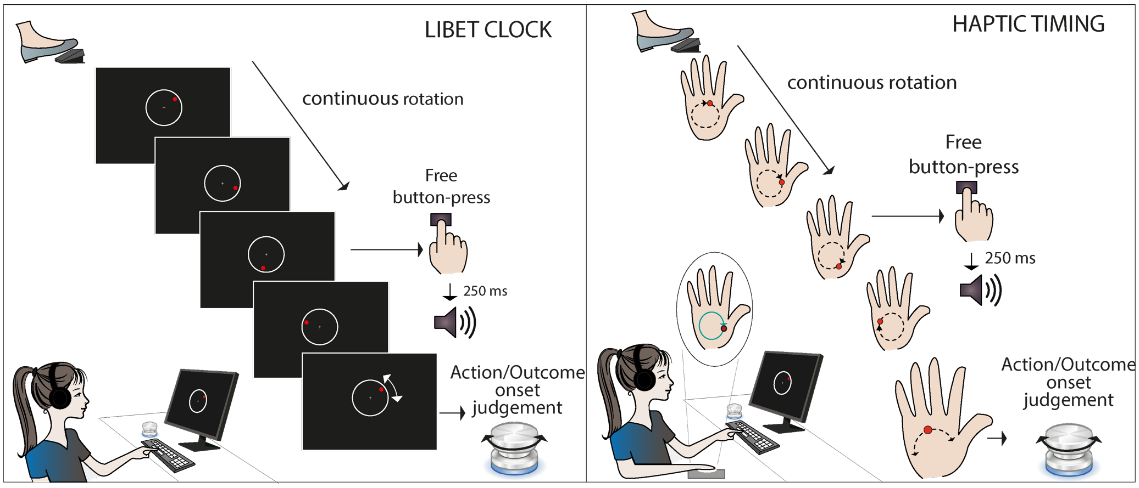


Figure 5.7 Experimental tasks of Study 2 for the two timing methods: Libet clock (left) and haptic clock (right).

5.3.3 Participants

Eighteen participants (one left-handed, three females, mean age=28.31 years old, SD=5.08) took part in the study. They had normal or corrected-to-normal vision. The local ethics committee approved this study, and participants were not paid for their participation. Two participants were excluded because of highly variable time judgement, leaving 16 participants for the analysis.

An a priori statistical power analysis was performed for sample size estimation in G*Power. Running a power analysis on a repeated measures ANOVA with two measurements (Libet clock and haptic clock, repeated four times corresponding to the four traditional blocks of the IB paradigm), a power of 0.80, an alpha level of 0.05, and a medium effect size (f= 0.47, η_p^2= 0.07) (Faul et al., 2007; Lakens, 2013) requires a sample size of approximately 16 participants. Thus, our proposed sample of 16 participants was adequate for the main objective of this study.

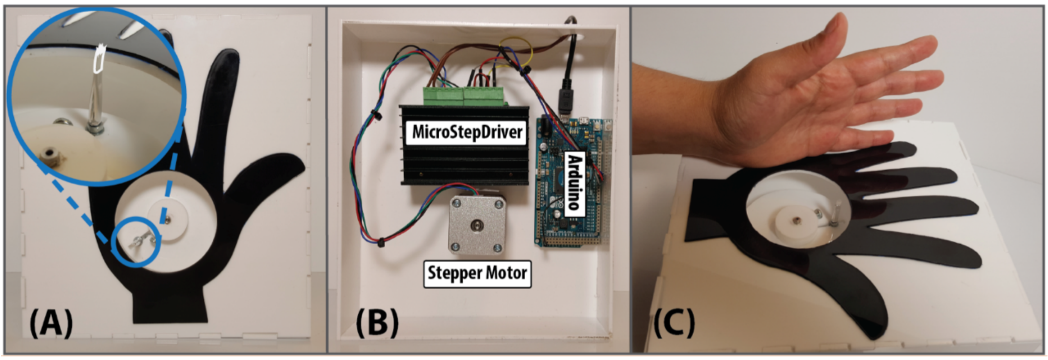


Figure 5.8 Custom-made box to provide haptic rotational stimulus. A 7cm in diameter orifice on top of the box allowed a brush (A) to rotate around participants' palm (C), using a step motor controlled by an Arduino board and a stepper driver (B).

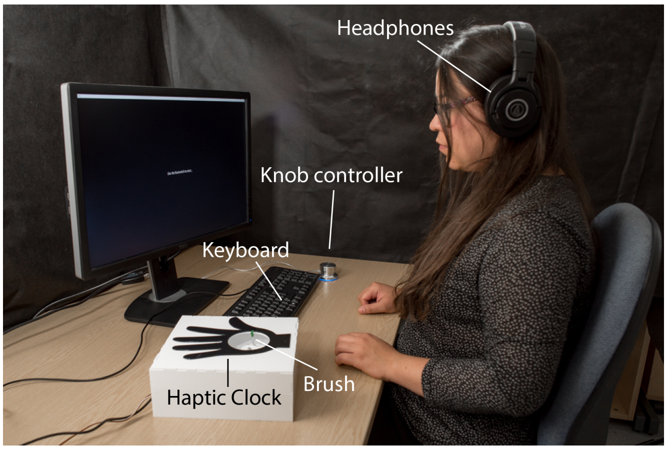


Figure 5.9 Experimental setup for Study 2.

5.3.4 Results on Intentional Binding

Before comparing our two main conditions (Libet clock and haptic clock), we first explored whether a binding effect was observed in each timing condition independently. To do so, we conducted repeated measures ANOVA tests to determine interactions between the baseline block (when only one event occurs, either action or outcome) and the active block (when both events occur – action and outcome) for both action binding and outcome binding (see Figure 2.3 for detailed blocks) in each timing condition.

In the Libet's clock condition, we found a significant binding effect ($F_{(1,454)}$=26.286, p<0.001, η2=0.055) for the action condition between baseline (M=8.4ms, SD=85.21ms) and active (M=33.13ms, SD=113.59ms) blocks. A significant binding effect was also found for the feedback condition ($F_{(1,460)}$=45.15, p<0.001, η2=0.089) between baseline (M=89.9ms, SD=131.46ms) and active (M=40.98ms, SD=117.17ms) bocks.

In the haptic clock condition we found significant binding effect ($F_{(1,457)}$=19.62, p<0.001, η2=0.041) for the action condition between baseline (M=66.34ms, SD=212.97ms) and active (M=121.93ms, SD=213.11ms) blocks. Similarly, a significant binding effect was found for the feedback condition ($F_{(1,391)}$=4.604, p=0.033, η2=0.012) when comparing baseline (M=190.93ms, SD=195.65ms) and active (M=159.06ms, SD=230.63ms) blocks.

These results show a significant temporal binding effect in each timing technique independently. Next, we present the comparison between the three timing techniques.

A one-way repeated measures ANOVA for each of the binding measures (action, outcome and total binding) was conducted across the two timing methods (i.e., Libet clock and haptic clock). The results show a non-significant effect of the timing methods on the total binding ($F_{(1, 13)}$= 0.675, p= 0.18, η_p^2= .014), and similar results are shown for action binding ($F_{(1, 13)}$= 1.400, p= 0.25, η_p^2= 0.1) and outcome binding ($F_{(1, 13)}$= 0.356, p= 0.56, η_p^2= 0.027). We found no significant difference on the binding effects (i.e., action, outcome and total binding) due to the timing methods used. Mean scores of action, outcome and total binding in each of the timing methods are presented in Figure 5.10.

	Action Binding	Outcome Binding	Total Binding
Libet Clock	23.61 ms (35.24 ms)	-54.56 ms (79.89 ms)	78.17 ms (94.79ms)
Haptic Clock	62.34 ms (118.54ms)	-32.23 ms (143.91 ms)	94.57 ms (142.3ms)

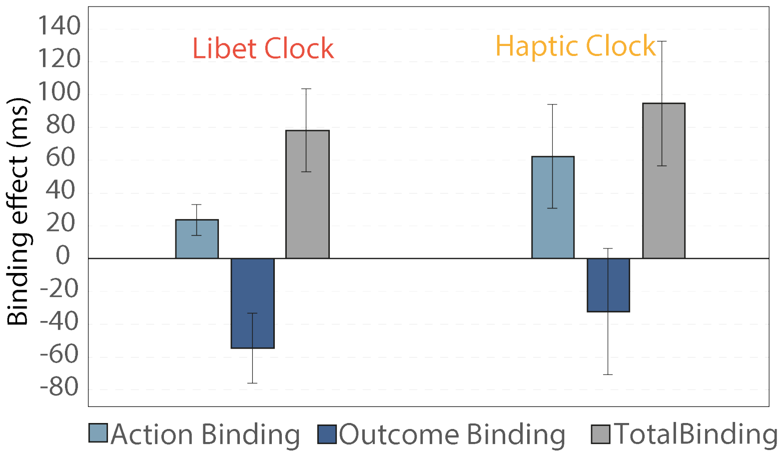


Figure 5.10 Results on intentional binding. Top: Average of action, outcome and total binding in milliseconds (with SD in brackets) grouped by timing method. Bottom: Plot for comparison – a positive value represents a delayed awareness while a negative value an early awareness. Total Binding = Action Binding – Outcome Binding. Error bars represent standard error of mean (SEM).

5.3.5 Results on Emotion

As in Study 1, a factorial analysis (principal components analysis (PCA), applying a Varimax rotation with Kaiser normalization) was performed to obtain the three dimensions of emotion (pleasure, arousal and dominance) from our PAD scale. Figure 5.11 shows the obtained values (normalized) for each dimension. A one-way repeated measure ANOVA for each dimension of emotions (i.e., pleasure, arousal and dominance) was conducted to compare the effect of the two timing methods (i.e., Libet clock and haptic clock) on participants' emotions. The results show a non-significant effect of timing methods on the pleasure (p>0.5) and dominance ($p>0.5$) dimensions. However, a significant effect on arousal ($F_{(1, 12)}$=12.518 , p=0.004 , η_p^2= 0.51) was observed.

5.3.6 Discussion of Study 2

Our results show that the IB effect measured with a haptic clock in the form of a rotatory timing stimulus on participants' palm was not statistically different from that measured with the traditional Libet clock, both methods in an IB task consisting of a button press action and tone outcome. This suggests that participants' time judgement did not differ due to the timing method used (visual or haptic).

	Pleasure	Arousal	Dominance
Libet Clock	0.42 (0.64)	0.20 (0.46)	0.48 (0.53)
Haptic Clock	0.53 (0.30)	0.81 (0.35)	0.56 (0.47)

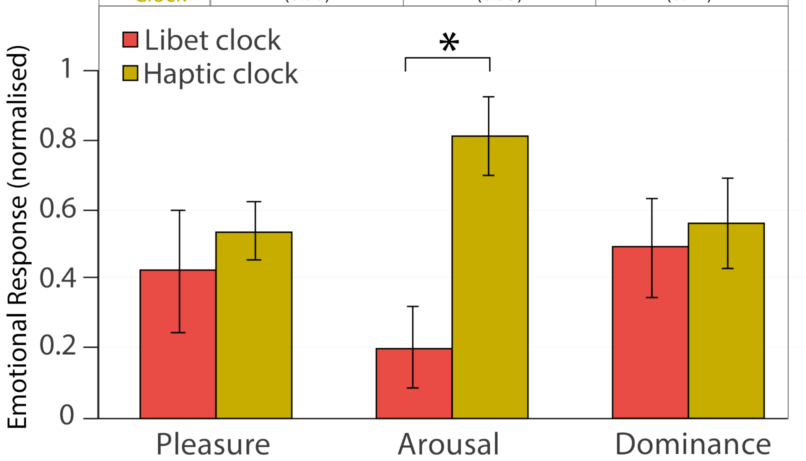


Figure 5.11 Results on emotions. Top: Average of the emotional responses from participants using the PAD scale grouped by timing method, with SD in brackets (values are normalized). Bottom: Plot for comparison of the three emotional dimensions (pleasure, arousal and dominance) per timing type. Error bars represent standard error of mean (SEM).

We introduced a *haptic timing* stimulus for use in the IB paradigm to reduce the amount of visual information presented to participants. Our results suggest that tactile cues on the hand can be used as an alternative to visual stimuli to measure perception of time. The human hand is highly sensitive due to mechanoreceptive units in the glabrous skin area (Johansson & Vallbo, 1979), and its resolution ranges from 1mm to 2mm (Johnson & Phillips, 1981). This property represents a promising tool to judge causally related events in time based on tactile position. In our experiment, participants were able to recognize spatio-temporal stimulation for voluntary action with an overall accuracy of 69ms, that is, the judgement error set as the difference between actual and perceived time in the baseline active block (where participants reported the action only.)

In contrast to the audio alphabet resolution (250ms), the haptic clock provides higher resolution as it represents a continuous stimulation. Although tactile sensitivity may be affected by sensory habituation (i.e., due to constant tactile stimuli) (Schmid et al., 2014), our participants did not report feeling habituated to the stimuli. The haptic clock condition took about 20min with four breaks of 2min between IB conditions (baseline and active). However, habituation may affect sensitivity for longer periods.

While the haptic clock also involved rotatory cues as in the visual Libet clock condition, it provides a timing strategy that reduces the visual information for timing stimuli. Furthermore, our results provide insights on exploring *haptic timing* using different and unpredictable patterns, for instance, different shapes, random path trajectories or different body parts (e.g., wrist). However, this needs to be further investigated.

One limitation of the haptic clock condition is that participants' hands were placed in a fixed position. Our experimental setup, however, was mainly focused on exploring tactile stimulation to measure time perception based on haptic position. Yet, our results provide intuition to present tactile stimulation in different ways, for example, through vibration using wearables gloves or in mid-air through ultrasound to avoid user instrumentation.

The analysis of emotional responses from participants shows non-significant differences in the two timing methods regarding the pleasure and dominance dimensions. However, our results suggest that participants felt significantly more aroused when using the haptic clock timing compared with the typical visual Libet clock. Similarly to Study 1, participants reported lack of engagement in the Libet clock condition, as reflected in the arousal dimension (see Figure 5.11) being significantly lower than in the haptic clock timing. In contrast, when using the haptic clock, they experienced being more “excited” and “stimulated” based on the bipolar adjectives from the PAD scale (see Appendix 3). This suggests that *haptic timing* could be suitable for tasks requiring more engagement.

5.4 General Discussion

In this chapter, we introduced *audio* and *haptic timing* to measure SoA using the IB paradigm. Our methods address limitations of current agency measures, in particular that they involve high visual information and are difficult to stay engaged with. Our timing techniques allowed us to measure perception of time through audio commands (audio alphabet) and rotating haptic stimulation on the hand (haptic clock) in an IB task, reducing the required visual cues. The results from two studies comparing our methods with the traditional visual timing stimulus (Libet clock and visual alphabet) show non-significant differences in time perception and thus on IB effect. Each timing condition relies on a different modality (i.e., vision, audition or touch) with different cognitive implications. However, those perceptual differences between the senses did not significantly bias the IB measurements, as shown in our analysis. Yet, the absolute difference in the means across timing types shows lower binding for the Libet clock, although this was not found to be significant.

Our results on emotion suggest that timing through audio and touch could provide a more suitable strategy for use in interactive scenarios. Our participants reported higher arousal and dominance when using the audio alphabet and haptic clock. This suggests that our methods not only provided a measure of agency but also improved engagement during the task, unlike the traditional Libet clock, which was associated with a low arousal dimension.

Previous studies on agency have demonstrated that IB is modulated by affective signals, being higher when a positive emotion is involved compared with a negative emotion (Aarts et al., 2012). Although the results from the PAD scale showed higher positive dimensions in arousal (not valence) for *audio* and *haptic timing*, this did not influence IB. This is in accordance with (Aarts et al., 2012), where IB was modified by the valence dimension only.

Our work thus opens opportunities to measure agency in active and visual scenarios, expanding research on the SoA in the field of HCI. The advantage of extending agency measures is being able to improve agency in actual HCI applications in which a user performs voluntary actions, namely, input commands, and thus design systems that do not disrupt users' feeling of being in control.

For instance, VR studies have shown that visual distortions can be beneficial to enhance user experiences. One example is "haptic retargeting" (Azmandian et al., 2016) in which visuomotor mismatch is introduced to provide the experience of grabbing several objects when actually grabbing only one. This helps to reduce the number of haptic proxies while enhancing the visuotactile experience. In another example, (Montano Murillo et al., 2017) employed visual space distortion to improve ergonomics while touching virtual objects in mid-air. By using this visual mismatch (also called retargeting), users were able to touch objects from a more comfortable position (avoiding fatigue), while preserving the original visual spatial position of virtual elements. Moreover, (Montano Murillo et al., 2017) used scaling factors in the displacement of VR navigation in order to create the perception of traveling greater distances when actually interacting in a reduced space. That is, users walk 1m in the real world when the visual representation in VR shows a displacement of 2m. Although this visual effect is known to induce simulator sickness (Kolasinski, 1995), it can optimise the navigable space, improving user experiences.

While some of these techniques are claimed to be imperceptible by the user, the role on the SoA in these scenarios has been unexplored, and therefore it is unclear if adding these kinds of visual distortions commonly used in VR environments affects the user's SoA.

The work presented in this chapter thus aims to offer alternative variants of timing stimuli in the IB paradigm, that is, a tool that HCI researchers can use and adapt (going through different sensory modalities) in specific applications. The Libet clock method has been widely used and extensively validated, but in situations where the Libet clock does not fit the visual layout (involving relevant visual information), *audio* or *haptic timing* could be used.

5.5 Conclusion and Limitations

Current research on agency in the field of HCI has been limited by agency measures based on subjective judgement. While the IB paradigm provides an implicit measure of the SoA, use of the Libet clock has limitations regarding high visual demand. Here, we provide two alternative techniques that employ *audio timing* through voice commands and *haptic timing* through tactile stimulation on the hand. Our techniques allow measuring perception of time in an IB task, revealing non-significant differences to the traditional visual method (Libet clock), but addressing high visual demand and lack of engagement. We believe this work will enable agency implication in HCI applications. Measuring users' SoA in broader modalities will allow the exploration of interaction techniques that give users an instinctive sense of control over the environment.

Chapter 6
Conclusions

The aim of this thesis was to explore how the experience of agency can be influenced by different human-computer interaction (HCI) paradigms. Common user experience (UX) frameworks that determine how to design a good user interface include a number of aspects related to performance metrics (e.g., accuracy, error, learning time) and user satisfaction scales (enjoyability, comfort, frustration, etc.) (Hartson & Pyla, 2012). However, despite the importance of developing technology that gives users a sense of being in control (Shneiderman, 2005), the sense of agency (SoA) has been little studied in HCI.

The goal of HCI is to bridge the "gulf of execution" (i.e., the separation between user's intentions and computer state changes) and the "gulf of evaluation" (i.e., the mismatch between the computer's actual state and user's expectations) (Norman, 1986). That is, HCI mainly involves an interplay between user input and system feedback (i.e., a communication dialogue (Hornbæk & Oulasvirta, 2017)). Since the sense of agency (SoA) is closely related to causality (an interplay between actions and outcomes), exploring users' experience of agency can help us to find better ways to bridge these gaps. In other words, measuring agency can award greater insights on how the experience of control is given by users' perception that sensory outcomes from the system are produced by their own actions.

Throughout this thesis, we have measured agency in various interaction paradigms, including mid-air interactions and olfactory interfaces. Next, we present a summary of the findings and contributions of this thesis based on the research questions stated in the Introduction chapter. Then, based on the results found in our studies, we highlight two relevant aspects: (1) the importance of agency measures in HCI and (2) the importance of preserving users' responsibility when designing user interfaces. We then finalise this chapter by presenting some limitations and possibilities for future work.

RQ1: Is a SoA experienced in touchless interaction?

In Chapter 3 we explored whether touchless interaction produces a user's SoA in comparison with physical interaction. Two types of action were implemented: a click gesture recorded by a Leap Motion optical sensor and a physical button press input using a typical keyboard. By measuring IB using the Libet clock method, we found a significant action binding effect in both types of input modality.

While touchless systems are widely employed in HCI, it is unclear whether users perceive a feeling of control while using gestural input commands. In this chapter, we contribute a study that validates touchless actions being perceived as responsive using implicit measures of agency. That is, although touchless input commands do not involve the typical cues of touching a real object, users can feel agency since touchless input involves a motor movement that is confirmed by feedback.

RQ2: What type of feedback produces greater SoA in mid-air interfaces?

In response to the two types of action tested (gestural and physical), visual, auditory and haptic outcomes were also compared in Chapter 3, aiming to explore what type of feedback is more suitable in touchless interaction. Our results suggest that auditory and haptic feedback produced a greater IB effect compared with visual feedback only.

With these results, we contribute insights into potential applications that user interface designers could employ, for example, in virtual reality (VR) and in-vehicle interaction, taking into consideration the SoA when developing mid-air interfaces.

RQ3: Do emotions produced by odours modulate the SoA?

In Chapter 4, we then explored whether the SoA is modulated by olfaction-mediated emotions. To achieve this goal, we employed a computer-controlled smell delivery device to deliver essential fragrances to subjects' nose and thus elicit different emotions due to scent exposure. We validated that the scents we used (lavender, civet and water) produced the intended emotion in participants, namely, positive negative and neutral, respectively, using a SAM scale. We also validated that the olfactory stimulation produced a physiological response by measuring participants' skin resistance. Then, by measuring IB using the Libet clock method, we found that IB was modulated by the different scents' conditions. These findings contribute to the literature of agency modulation through affective information (via visual, auditory and tactile cues). However, here we provide evidence of agency modulation by affective information via olfactory channel.

RQ4: Does a positive smell increase the SoA?

In line with previous research suggesting that agency increases when a positive emotion is involved, our results presented in Chapter 4, also show that exposure to the scent of lavender (rated significantly higher in valence than the civet scent) produced significantly stronger IB. With these findings, we contribute insights on how our results can have implications in HCI applications such as in-vehicle interfaces and sensory substitution.

RQ5: Can the IB paradigm be employed using a non-visual timing stimulus?

Since implicit agency measures can employ visual timing cues that require relevant visual attention (e.g., the Libet clock), it is often challenging to assess agency in tasks involving significant visual information (e.g., in VR). To address this limitation, in Chapter 5 we first developed two novel timing techniques based on audio and tactile cues to be used as a reference of time to report occurrence of events. We then assessed IB using our new techniques and found a significant binding effect measured with auditory and haptic timing. These novel methods contribute modality variants for agency measurements, addressing visual demand.

RQ6: Do non-visual timing stimuli reduce lack of engagement?

In Chapter 5, we also compared our audio and haptic timing methods with traditional visual timing techniques in terms of self-reported emotion. We employed a PAD scale which involves a variety of bipolar adjectives to obtain the three dimensions of emotion. This evaluation showed that audio and haptic timing produced higher self-reports of arousal and dominance than visual timing. With these findings, we contribute timing techniques able to measure IB that could be more appealing for application in more interactive and visual tasks.

6.1 Agency as a Measure in Human-Computer Interaction

Since the SoA has been suggested to reflect an experience of being in control (Haggard, 2017), recent studies have measured SoA as a means to explore users' feeling of controlling a system (Coyle et al., 2012; Limerick et al., 2015; Bergstrom-Lehtovirta et al., 2018). Indeed, measuring agency in the studies described throughout this thesis has provided interesting insights.

For instance, in Chapter 3 we found IB for touchless systems involving input commands that do not require any physical contact at all. Mid-air interfaces are becoming very common to control computers and machines, and therefore many commercial devices are being released. In Chapter 3 we show by implicitly measuring the SoA that it is not necessary to physically touch an object (e.g., press a button) to perceive we are activating a command. Rather, a simple mid-air gesture (e.g., a finger movement mimicking a button press) can serve as an input modality that allows users to feel agency.

We also showed that appropriate multisensory cues can improve the SoA. For instance, in Chapter 4 we found that pleasant odours increase IB, which can provide major benefits for automotive interfaces and VR (increasing realism). Our results might explain why scent presentation in driving scenarios is known to improve user performance (Baron & Kalsher, 1998). By modulating users' emotions through affective olfactory cues, we can enhance users' sense of control.

Measuring agency can give broader evidence on how to design user interfaces that provide users with a feeling of being in control. However, measuring agency is often challenging since current agency measures are limited to simple micro-interactions, such as a button press. However, by expanding the research on agency implications in HCI, we can broaden the possibility to assess agency in more complex settings. For instance, in Chapter 5 we expanded implicit agency measures by exploring timing cues perceived by different senses, with the aim to study agency in more interactive tasks.

With the results described in this thesis, we aspire to advance the understanding of agency implication in the use of technology. We believe that agency measures should be included within UX metrics to design systems that not only consider precision and usability but that also support both (1) a feeling of being an agent and (2) a feeling of being responsible for events. This consideration might have a greater benefit in emerging technology using autonomous systems and artificial intelligence (AI).

6.2 Agency and Responsibility in Human-Computer Interaction

The ubiquity of technology in our everyday life is introducing many autonomous systems. For instance, the rapid development of AI (e.g., autonomous driving (Hengstler et al., 2016)) has created shared control between humans and machines. Although assisted systems can improve users' performance and SoA (Wen et al., 2015; Inoue et al., 2017), high assistance levels can also disrupt this experience. A decrease in the SoA can cause the operator not to self-attribute the outcomes of their actions, thus reducing the sense of responsibility, which raises the question, "who is in control now?" (Berberian et al., 2012). Since "the cognitive coupling between human and machine remains difficult to achieve" (Berberian, 2019), autonomous systems should be carefully designed so that users maintain an appropriate sense of responsibility. In other words, it is important that systems let users clearly experience what they are doing.

Recent research is exploring the role of agency in legal responsibility (Haggard & Tsakiris, 2009; Haggard, 2017), entailing that the ethical implications of autonomous systems are being considered within legal systems (Elish, 2019). This exploration must be done from a design perspective in HCI. That is, the development of new technology should in fact support a feeling of being in control, not only with the goal of increasing usability and enhancing user experiences but also with that of supporting ethical responsibility.

6.3 Limitations and Future Work

The studies conducted in this work mainly involved simple micro-interactions consisting of discrete actions (e.g., a button press). This is because, according to the IB paradigm, when subjects report the time at which events occur, these events should be easily notable (i.e., discrete). For more complex actions, however, (e.g., a continuous hand movement) measuring IB could be challenging. Nonetheless, some studies have reported agency assessment during continuous action consisting of repeated key presses using self-reports of explicit agency (Wen et al., 2015; Inoue et al., 2017). Therefore, for future work, we will explore implicit agency measures for more complex actions involving continuous movements of different parts of the body (e.g., by using full-body tracking).

Another limitation is that in our studies we focused more on assessing implicit agency rather than explicit agency, in other words, using the IB paradigm to study agency in HCI. This is because we paid more attention to how the experience of control is given by users' perception that sensory feedback from the system is produced by users' own actions, in line with prior research studying agency in different input modalities. However, for future work, we will make a more direct comparison between implicit and explicit judgements of agency to explore whether there is a correlation between IB and self-reports in mid-air interaction and olfactory interfaces.

In Chapter 4 we used smell stimulation as priming (i.e., participants were presented with a scent at the beginning of the IB task) rather than as an outcome. We based this design on the work by (Aarts et al., 2012), in which brief exposure to a positive cue affected IB. However, recent research is exploring smell notifications (Maggioni et al., 2018) that serve as feedback from the system. For example, the user is working on the computer, and when someone sends them an email, instead of receiving a visual or auditory notification, a scent is released to notify them of the email's arrival. Scents can also vary depending on the sender. Based on this evidence, in future work we will explore IB using olfactory outcomes trying to address challenges related to delivery timing and synchronization, since olfactory perception can be slower than visual or auditory perception (Olofsson, 2014).

Based on our results in Chapter 5, the follow-up work is to carry out evaluations of our timing methods in actual HCI applications, particularly in VR. Some examples include a) how much visual scaling factors affect user's SoA in navigation techniques (Montano Murillo et al., 2017; Tregillus et al., 2017); b) to what extent the experience of agency is modified by retargeting techniques (Azmandian et al., 2016) without losing significant feeling of control; and c) how to measure illusion of agency in more complex displays such as gestural interaction and mid-air haptic feedback (e.g., training simulators or videogames). For instance, we may say that video gamers perceive SoA while interacting with a virtual environment even when they are just observing a virtual representation of their body.

Appendix 1

Olfactory Assessment Test

University of Sussex

Thank you for volunteering to take part in this experiment. Before the experiment can begin, we need to confirm few personal details to ensure that you match the study population selection criteria, and to ensure that it is safe for you to participate. Therefore, please answer the following questions: (Note that this information will be treated in strict confidence at all times)

1. What is your age? ____________

2. In this moment, are suffering of cold, hay fever or any other temporary respiratory problems? YES / NO

3. Do you suffer of asthma or any kind of severe allergy since birth? YES / NO

4. Do you suffer of any respiratory problems? YES / NO

5. Do you suffer of fainting fits? YES / NO

6. If you think there is any other relevant information about your health to be aware of for this experiment you are strongly required to specify it in the following space.

____

7. Have you experienced smell distortions within the past 2 years? YES / NO

8. Have you ever, chronically or frequently, had any of the following conditions: *sneezing/itchy nose; nasal discharge; problems breathing through nose; sinus pain/headache; sinus infection; nasal polyps as adult; gland behind nose as child; deviated septum; nosebleeds; allergic nasal symptoms; coughing; breathing problems; frequent colds; allergic asthma; non-allergic asthma; attacks of breathing difficulties/wheezing; lower respiratory mucus; lower respiratory infection; other problems with nose/mouth/sinuses/lower airways*. YES / NO

9. Have you ever experienced prolonged or serious exposure to any of the following? herbicides/pesticides; metal dust; acid fumes; industrial solvents/cleaning products; wood dust; formaldehyde; other exposure? YES / NO

10. Have you ever been allergic or hypersensitive to any of the following substances or products: *seasonal allergy; perennial allergy; medication; food; other allergy/hyper reactivity*? YES / NO

11. Have you ever had any serious head trauma or facial injury? YES / NO
    If so, did you have a head injury? YES / NO
    If so, did you have a facial injury? YES / NO

12. Have you ever had any of the following diseases/conditions/symptoms: *epilepsy; stroke; frequent earaches; high blood pressure; diabetes mellitus; Bell's palsy; rheumatism; cystic fibrosis; Alzheimer's disease; Parkinson's disease; alcohol abuse; drug abuse; psychiatric problems; multiple sclerosis; depression; Sjo¨gren's syndrome;*

cancer/tumour; pregnancy/delivery; other disease/condition/symptom? YES / NO

13. Have you ever had any of the following surgeries: *deviated nasal septum repair; nasal polypectomy as adult; removal of gland behind nose as child; nasal plastic surgery; other nasal surgery; sinus surgery; other head/face surgery; brain surgery; mouth surgery; removal of wisdom tooth; other tooth surgery; ear surgery; removal of tonsil*? YES / NO

14. Have you ever smoked? YES / NO

15. Do you currently smoke? YES / NO

16. How much do you smoke or did you smoke in your last year as a smoker?
< 1 *pack per day* / *1-2 packs per day* / *> 2 packs per day.*

17. Have you ever experienced prolonged exposure to tobacco smoke in your home or working environment (passive smoking)? YES / NO

18. Are you annoyed by or do you get symptoms from strong odours, for example perfumes, cleaning agents and flowers? YES / NO

19. If so, to what extent are you annoyed or do you get symptoms?
no symptoms / *mild symptoms* / *moderate symptoms / severe symptoms*. /// *nose / eyes / throat / lungs / other symptoms.*

FEMALE QUESTIONNAIRE (discretionary)

Please answer the following questions:

(Note that this information will be treated in strict confidence at all times, please leave blank the following questions if you are not comfortable in answering)

1. When did you last have your menstrual cycle? (date of the first day, approximately) ______

2. Are you using any hormonal contraceptives? YES / NO

At the end of the experiment, the experimenter will tell you its purpose, and will be happy to answer any questions about the experiment. Your data will be treated in strict confidence all times. If at any stage during or following the experiment, you would like to exclude yourself and your data from the study, you are welcome to do so any time during the experiment you feel uncomfortable and would prefer to leave, please feel free to do so, by letting the experimenter know. However, if you would like to withdraw from the study will be possible until the research passed the data analysis stage (approximately 1 month after the data acquisition).

Please confirm that you agree with us retaining this information by signing below:

Full Name: ____

Signature: ____ Date:

Appendix 2

SAM Emotional Scale

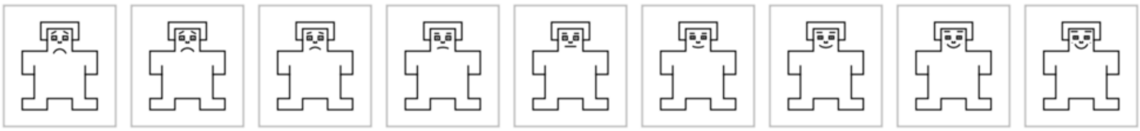
This scale aims to measure your emotional valence, arousal and dominance.

Please indicate your emotional response on the scale.

Gender: _________

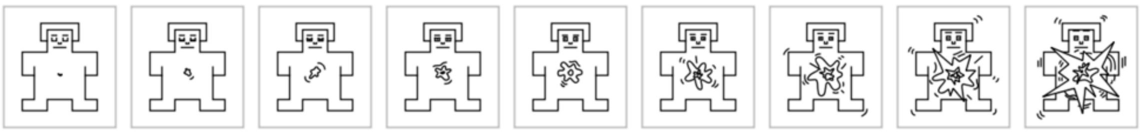
Age: ____________

Emotional Valence (**Negative vs. Positive**)



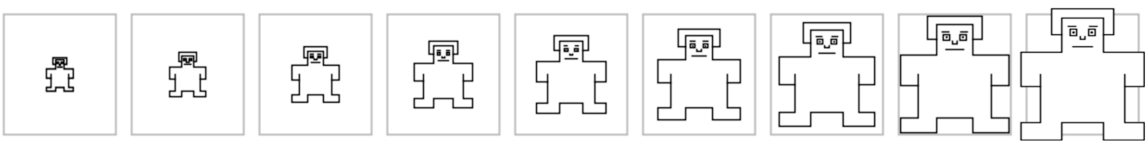
1 2 3 4 5 6 7 8 9

Arousal (**Low vs. High**)



1 2 3 4 5 6 7 8 9

Dominance (**Low vs. High**)



1 2 3 4 5 6 7 8 9

Appendix 3

PAD Emotional Scale

This scale aims to measure your emotional response and sense of control while performing an action and receiving a sensory feedback.

Please indicate your emotional response on the scale.

Gender: _________

Age: ____________

	1	2	3	4	5	6	7	
Happy								Unhappy
Stimulated								Relaxed
Controlling								Controlled
Pleased								Annoyed
Excited								Calm
Influential								Influenced
Satisfied								Unsatisfied
Frenzied								Sluggish
In control								Cared for
Contented								Melancholic
Jittery								Dull
Important								Awed
Hopeful								Despairing
Wide awake								Sleepy
Dominant								Submissive
Relaxed								Bored
Aroused								Unaroused
Autonomous								Guided

(Mehrabian & Russell, 1974) reported that the items (18 bipolar adjective pairs) composing the PAD scale measure the three main dimensions of emotions (higher order factors): pleasure (valence), arousal and dominance. To test whether those three dimensions can be extracted from our PAD results a factorial analysis (Principal Components Analysis-PCA, applying a Varimax rotation with Kaiser normalization) was performed. Factorial analysis statistically measures the correlations between items to determine which are assumed to be measuring similar dimensions (higher order factors). The factorial analysis results in Table 2 show the division of the data in three dimensions (factors) that are composed of the adjective pairs grouped together by the highest of their factor values (in bold) as best representation of each factor. For this very reason three factors are extracted (using Bartlett Scores Method), which together explain 67% of the total variance. Additionally, internal consistency for each extracted factor was exanimated using Cronbach's alpha (α) coefficient. Our extracted factors showed good internal consistency values, in accordance with previous work (Cronbach, 1951) that identified the range $0.9 > \alpha \geq 0.8$ as good coefficient (see Table 2 for the results details of each factor).

Bipolar Adjective Pair	**Factor**		
	1. Pleasure (α: 0.849)	**2. Dominance** (α: 0.866)	**3. Arousal** (α: 0.880)
1. Happy- Unhappy	**0.718**	0.085	0.405
2. Pleased - Annoyed	**0.656**	0.530	0.263
3. Hopeful - Despairing	**0.665**	0.493	-0.119
4. Satisfied - Unsatisfied	**0.869**	0.269	-0.019
5. Relaxed - Bored	**0.483**	0.141	0.247
6. Contented - Melancholic	**0.601**	0.154	0.064
7. Autonomous - Guided	0.151	**0.748**	0.050
8. Influential - Influenced	0.075	**0.789**	0.409
9. In control – Cared for	0.508	**0.651**	0.231
10. Dominant - Submissive	0.576	**0.660**	0.482
11. Controlling - Controlled	0.161	**0.798**	0.124
12. Important - Awed	0.190	**0.480**	0.354
13. Simulated - Relaxed	0.144	-0.064	**0.910**
14. Exited - Calm	0.211	0.199	**0.901**
15. Frenzied - Sluggish	0.194	0.286	**0.497**
16. Jittery - Dull	0.022	0.493	**0.647**
17. Wide awake - Sleepy	0.049	0.445	**0.751**
18. Aroused - Unaroused	0.101	0.417	**0.792**

Table S1. Factorial compositions of the PAD Scale (PCA rotated matrix factor matrix) on the three dimensions (factors) of emotions, Cronbach's alpha (α) values for each extracted factor.

Appendix 4

This appendix shows pictures and screenshots of the experimental setup used in Chapter 4 and Chapter 5, where audio and haptic timing where explored.

Figure S1. Experimental setup for the olfactory study.

Figure S2. Experimental setup used for the Libet clock condition (left) and the Visual Alphabet condition (right).

Figure S3. Experimental setup used for the Haptic clock condition.

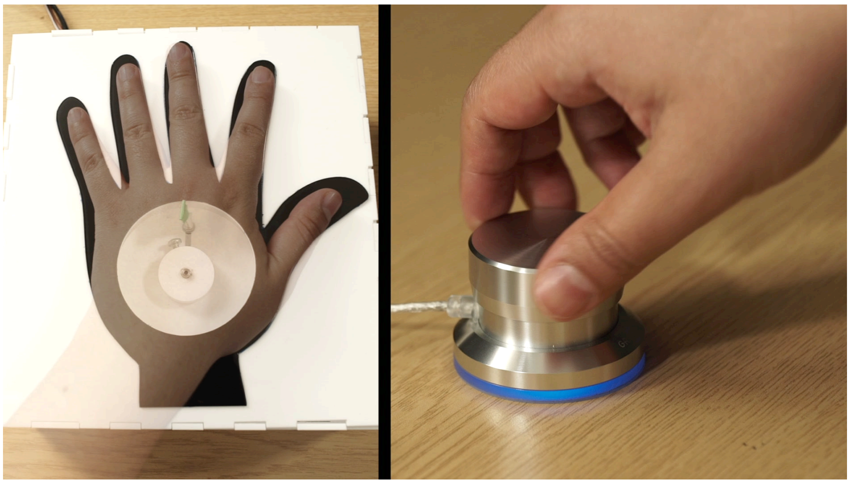


Figure S4. Hand position report. Participants reported the position of the haptic cue on their hand by rotating an external controller that controlled the brush position.

References

Aarts, H., E. Bijleveld, R. Custers, M. Dogge, M. Deelder, D. Schutter and N. E. van Haren (2012). "Positive priming and intentional binding: Eye-blink rate predicts reward information effects on the sense of agency." Social neuroscience **7**(1): 105-112. doi: https://doi.org/10.1080/17470919.2011.590602.

Agarwal, A. and A. Meyer (2009). Beyond usability: evaluating emotional response as an integral part of the user experience. CHI'09 Extended Abstracts on Human Factors in Computing Systems, ACM. doi: DOI: https://dx.doi.org/10.1145/1520340.1520420.

Aggleton, J. P. and M. Mishkin (1986). The amygdala: sensory gateway to the emotions. Biological foundations of emotion, Elsevier**:** 281-299. doi: https://doi.org/10.1016/B978-0-12-558703-7.50018-8.

Alexander, P., A. Schlegel, W. Sinnott-Armstrong, A. L. Roskies, T. Wheatley and P. U. Tse (2016). "Readiness potentials driven by non-motoric processes." Consciousness and cognition **39**: 38-47. doi: DOI: https://dx.doi.org/10.1016/j.concog.2015.11.011.

Amores, J. and P. Maes (2017). Essence: Olfactory interfaces for unconscious influence of mood and cognitive performance. Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, ACM. doi: http://dx.doi.org/10.1145/3025453.3026004.

Asley, S. (2014). Touch-less control coming cars. automotive engineering, SAE**:** 20-23. http://www.visteon.com/media/touchless.pdf

Atsumi, T. and K. Tonosaki (2007). "Smelling lavender and rosemary increases free radical scavenging activity and decreases cortisol level in saliva." Psychiatry Research **150**(1): 89-96. doi: https://doi.org/10.1016/j.psychres.2005.12.012.

Awad, E., S. Dsouza, R. Kim, J. Schulz, J. Henrich, A. Shariff, J.-F. Bonnefon and I. Rahwan (2018). "The Moral Machine experiment." Nature **563**(7729): 59-64. doi: https://doi.org/10.1038/s41586-018-0637-6.

Azmandian, M., M. Hancock, H. Benko, E. Ofek and A. D. Wilson (2016). Haptic retargeting: Dynamic repurposing of passive haptics for enhanced virtual reality experiences. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM. doi: DOI: https://dx.doi.org/10.1145/2858036.2858226.

Babcock, L. and G. Loewenstein (1997). "Explaining bargaining impasse: The role of self-serving biases." Journal of Economic perspectives **11**(1): 109-126. doi: http://dx.doi.org/10.1037/h0076486.

Banakou, D., R. Groten and M. Slater (2013). "Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes." Proceedings of the National Academy of Sciences **110**(31): 12846-12851. doi: https://doi.org/10.1073/pnas.1306779110.

Banakou, D. and M. Slater (2014). "Body ownership causes illusory self-attribution of speaking and influences subsequent real speaking." Proceedings of the National Academy of Sciences **111**(49): 17678-17683. doi: ttps://doi.org/10.1073/pnas.1414936111.

Bandura, A. (2001). "Social cognitive theory: An agentic perspective." Annual review of psychology **52**(1): 1-26. doi: https://doi.org/10.1146/annurev.psych.52.1.1.

Bandura, A. (2002). "Selective moral disengagement in the exercise of moral agency." Journal of moral education **31**(2): 101-119. doi: https://doi.org/10.1080/0305724022014322.

Barfield, W. and E. Danas (1996). "Comments on the use of olfactory displays for virtual environments." Presence: Teleoperators & Virtual Environments **5**(1): 109-121. doi: https://doi.org/10.1162/pres.1996.5.1.109

Baron, R. A. and M. J. Kalsher (1998). "Effects of a pleasant ambient fragrance on simulated driving performance: the sweet smell of... safety?" Environment and Behavior **30**(4): 535-552. doi: https://doi.org/10.1177/001391659803000407.

Barrett and Holland. Available from: https://www.hollandandbarrett.com/.

Bartoli, L., F. Garzotto, M. Gelsomini, L. Oliveto and M. Valoriani (2014). Designing and evaluating touchless playful interaction for ASD children. Proceedings of the 2014 conference on Interaction design and children, ACM**:** 17-26. doi: http://dx.doi.org/10.1145/2593968.2593976.

Baudel, T. and M. Beaudouin-Lafon (1993). Charade: remote control of objects using free-hand gestures. Communications of the ACM. **36:** 28-35. doi: http://dx.doi.org/10.1145/159544.159562.

Beck, B., S. Di Costa and P. Haggard (2017). "Having control over the external world increases the implicit sense of agency." Cognition **162**: 54-60. doi: https://doi.org/10.1016/j.cognition.2017.02.002.

Bensafi, M., C. Rouby, V. Farget, B. Bertrand, M. Vigouroux and A. Holley (2002). "Autonomic nervous system responses to odours: the role of pleasantness and arousal." Chemical Senses **27**(8): 703-709. doi: https://doi.org/10.1093/chemse/27.8.703.

Berberian, B. (2019). "Man-Machine teaming: a problem of Agency." IFAC-PapersOnLine **51**(34): 118-123. doi: https://doi.org/10.1016/j.ifacol.2019.01.049.

Berberian, B., J.-C. Sarrazin, P. Le Blaye and P. Haggard (2012). "Automation technology and sense of control: a window on human agency." PloS one **7**(3): e34075. doi: https://doi.org/10.1371/journal.pone.0034075.

Bergstrom-Lehtovirta, J., D. Coyle, J. Knibbe and K. Hornbæk (2018). I Really did That: Sense of Agency with Touchpad, Keyboard, and On-skin Interaction. Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, ACM. doi: https://doi.org/10.1145/3173574.3173952.

Bestgen, A.-K., P. Schulze and L. Kuchinke (2015). "Odor emotional quality predicts odor identification." Chemical Senses **40**(7): 517-523. doi: https://doi.org/10.1093/chemse/bjv037.

Bevan, N. (1995). Usability is quality of use. Advances in Human Factors/Ergonomics, Elsevier. **20:** 349-354. doi: https://doi.org/10.1016/S0921-2647(06)80241-8.

Bevan, N. (2001). "International standards for HCI and usability." International Journal of Human-Computer Studies **55**(4): 533-552. doi: https://doi.org/10.1006/ijhc.2001.0483.

Blakemore, S.-J., C. D. Frith and D. M. Wolpert (1999). "Spatio-temporal prediction modulates the perception of self-produced stimuli." Journal of cognitive neuroscience **11**(5): 551-559. doi: https://doi.org/10.1162/089892999563607

Blakemore, S.-J., D. Wolpert and C. Frith (2000). "Why can't you tickle yourself?" Neuroreport **11**(11): R11-R16.

Blakemore, S.-J., D. M. Wolpert and C. D. Frith (2002). Abnormalities in the awareness of action. Trends in cognitive sciences. **6:** 237-242. doi: http://dx.doi.org/10.1016/S1364-6613(02)01907-1.

Bohil, C. J., B. Alicea and F. A. Biocca (2011). "Virtual reality in neuroscience research and therapy." Nature reviews neuroscience **12**(12): 752. doi: https://doi.org/10.1038/nrn3122.

Borhani, K., B. Beck and P. Haggard (2017). "Choosing, doing, and controlling: implicit sense of agency over somatosensory events." Psychological science **28**(7): 882-893. doi: https://doi.org/10.1177/0956797617697693.

Bradley, G. W. (1978). "Self-serving biases in the attribution process: A reexamination of the fact or fiction question." Journal of personality and social psychology **36**(1): 56. doi: http://dx.doi.org/10.1037/0022-3514.36.1.56.

Bradley, M. M. and P. J. Lang (1994). "Measuring emotion: the self-assessment manikin and the semantic differential." Journal of behavior therapy and experimental psychiatry **25**(1): 49-59. doi: https://doi.org/10.1016/0005-7916(94)90063-9.

Brauchli, P., P. B. Rüegg, F. Etzweiler and H. Zeier (1995). "Electrocortical and autonomic alteration by administration of a pleasant and an unpleasant odor." Chemical Senses **20**(5): 505-515. doi: https://doi.org/10.1093/chemse/20.5.505.

Brewster, S., D. McGookin and C. Miller (2006). Olfoto: designing a smell-based interaction. Proceedings of the SIGCHI conference on Human Factors in computing systems, ACM. doi: https://doi.org/10.1145/1124772.1124869.

Brianza, G., A. Tajadura-Jiménez, E. Maggioni, D. Pittera, N. Bianchi-Berthouze and M. Obrist (2019). As light as your scent: effects of smell and sound on body image perception. IFIP

Conference on Human-Computer Interaction, Springer. doi: https://doi.org/10.1007/978-3-030-29390-1_10.
Buckwald, M. and D. David Holz (2010). Leap Motion, Inc., www.leapmotion.com
Buehner, M. J. (2005). "Contiguity and covariation in human causal inference." Learning & Behavior **33**(2): 230-238. doi: DOI: https://doi.org/10.3758/BF03196065.
Cadoz, C. (1994). Les réalités virtuelles.
Carter, T., S. A. Seah, B. Long, B. Drinkwater and S. Subramanian (2013). UltraHaptics: multi-point mid-air haptic feedback for touch surfaces. Proceedings of the 26th annual ACM symposium on User interface software and technology, ACM**:** 505-514. doi: http://dx.doi.org/10.1145/2501988.2502018.
Caspar, E. A., J. F. Christensen, A. Cleeremans and P. Haggard (2016). "Coercion changes the sense of agency in the human brain." Current Biology **26**(5): 585-592. doi: https://doi.org/10.1016/j.cub.2015.12.067.
Cavazzana, A., C. Begliomini and P. S. Bisiacchi (2014). "Intentional binding effect in children: insights from a new paradigm." doi: DOI: https://doi.org/10.3389/fnhum.2014.00651.
Cavazzana, A., C. Begliomini and P. S. Bisiacchi (2017). "Intentional binding as a marker of agency across the lifespan." Consciousness and cognition **52**: 104-114. doi: DOI: https://dx.doi.org/10.1016/j.concog.2017.04.016.
Chambon, V. and P. Haggard (2012). Sense of control depends on fluency of action selection, not motor performance. Cognition. **125:** 441-451. doi: http://dx.doi.org/10.1016/j.cognition.2012.07.011.
Chambon, V. and P. Haggard (2013). Premotor or Ideomotor: How Does the Experience of Action Come About? Action science: Foundations of an emerging discipline**:** 359. doi: http://dx.doi.org/10.1016/j.cognition.2012.07.011.
Chambon, V., D. Wenke, S. M. Fleming, W. Prinz and P. Haggard (2012). "An online neural substrate for sense of agency." Cerebral Cortex **23**(5): 1031-1037. doi: DOI: https://doi.org/10.1093/cercor/bhs059.
Chebat, D.-R., V. Harrar, R. Kupers, S. Maidenbaum, A. Amedi and M. Ptito (2018). Sensory substitution and the neural correlates of navigation in blindness. Mobility of Visually Impaired People, Springer**:** 167-200. doi: https://doi.org/10.1007/978-3-319-54446-5_6.
Choe, S. Y. and K.-H. Min (2011). "Who makes utilitarian judgments? The influences of emotions on utilitarian judgments." Judgment & Decision Making **6**(7).
Chrea, C., D. Valentin, C. Sulmont-Rossé, H. L. Mai, D. H. Nguyen and H. Abdi (2004). "Culture and odor categorization: agreement between cultures depends upon the odors." Food Quality and Preference **15**(7-8): 669-679. doi: https://doi.org/10.1016/j.foodqual.2003.10.005.
Christensen, J., M. Yoshie, S. Di Costa and P. Haggard (2016). "Emotional valence, sense of agency and responsibility: A study using intentional binding." Consciousness and cognition **43**: 1-10. doi: https://doi.org/10.1016/j.concog.2016.02.016.
Christensen, J. F., S. Di Costa, B. Beck and P. Haggard (2019). "I just lost it! Fear and anger reduce the sense of agency: a study using intentional binding." Experimental brain research **237**(5): 1205-1212. doi: https://doi.org/10.1007/s00221-018-5461-6.
Cohen, J. (1977). Statistical power analysis for the behavioral sciences (revised ed.), New York: Academic Press.
Cohen, J. (1988). "Statistical power analysis for the behavioral sciences . Hilsdale." NJ: Lawrence Earlbaum Associates **2**. https://www.taylorfrancis.com/books/9781134742707
Covarrubias, M., M. Bordegoni, M. Rosini, E. Guanziroli, U. Cugini and F. Molteni (2015). VR system for rehabilitation based on hand gestural and olfactory interaction. Proceedings of the 21st ACM Symposium on Virtual Reality Software and Technology, ACM. doi: http://dx.doi.org/10.1145/2821592.2821619.
Coyle, D., J. Moore, P. O. Kristensson, P. Fletcher and A. Blackwell (2012). I did that! Measuring users' experience of agency in their own actions. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM. doi: DOI: https://dx.doi.org/10.1145/2207676.2208350.

Croy, I., W. Maboshe and T. Hummel (2013). "Habituation effects of pleasant and unpleasant odors." International Journal of Psychophysiology **88**(1): 104-108. doi: https://doi.org/10.1016/j.ijpsycho.2013.02.005.

Danquah, A. N., M. J. Farrell and D. J. O'Boyle (2008). "Biases in the subjective timing of perceptual events: Libet et al.(1983) revisited." Consciousness and cognition **17**(3): 616-627. doi: https://doi.org/10.1016/j.concog.2007.09.005.

De Groot, J. H., G. R. Semin and M. A. Smeets (2014). "I can see, hear, and smell your fear: Comparing olfactory and audiovisual media in fear communication." Journal of Experimental Psychology: General **143**(2): 825. doi: http://dx.doi.org/10.1037/a0033731.

De la Peña, N., P. Weil, J. Llobera, E. Giannopoulos, A. Pomés, B. Spanlang, D. Friedman, M. V. Sanchez-Vives and M. Slater (2010). "Immersive journalism: immersive virtual reality for the first-person experience of news." Presence: Teleoperators and Virtual Environments **19**(4): 291-301.

De Pirro, S., P. Lush, J. Parkinson, T. Duka, H. D. Critchley and A. Badiani (2019). "Effect of alcohol on the sense of agency in healthy humans." Addiction Biology: e12796. doi: https://doi.org/10.1111/adb.12796.

De Vignemont, F. and P. Fourneret (2004). "The sense of agency: A philosophical and empirical review of the "Who" system." Consciousness and cognition **13**(1): 1-19. doi: https://doi.org/10.1016/S1053-8100(03)00022-9.

Demanet, J., P. S. Muhle-Karbe, M. T. Lynn, I. Blotenberg and M. Brass (2013). "Power to the will: how exerting physical effort boosts the sense of agency." Cognition **129**(3): 574-578. doi: https://doi.org/10.1016/j.cognition.2013.08.020.

Desmurget, M., K. T. Reilly, N. Richard, A. Szathmari, C. Mottolese and A. Sirigu (2009). "Movement intention after parietal cortex stimulation in humans." Science **324**(5928): 811-813. doi: https://doi.org/10.1126/science.1169896.

Dinh, H. Q., N. Walker, L. F. Hodges, C. Song and A. Kobayashi (1999). Evaluating the importance of multi-sensory input on memory and the sense of presence in virtual environments. Virtual Reality, 1999. Proceedings., IEEE, IEEE. doi: https://doi.org/10.1109/VR.1999.756955.

Dmitrenko, D., E. Maggioni and M. Obrist (2017). OSpace: towards a systematic exploration of olfactory interaction spaces. Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces, ACM. doi: https://doi.org/10.1145/3132272.3134121.

Dmitrenko, D., E. Maggioni, C. T. Vi and M. Obrist (2017). What did I sniff? Mapping scents onto driving-related messages. AutomotiveUI'17 Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, ACM. doi: https://doi.org/10.1145/3122986.3122998.

Dmitrenko, D., C. T. Vi and M. Obrist (2016). A comparison of scent-delivery devices and their meaningful use for in-car olfactory interaction. Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, ACM. doi: https://doi.org/10.1145/3003715.3005464.

Dong, S. and T. J. Jacob (2016). "Combined non-adaptive light and smell stimuli lowered blood pressure, reduced heart rate and reduced negative affect." Physiology & behavior **156**: 94-105. doi: https://doi.org/10.1016/j.physbeh.2016.01.013.

Eagleman, D. M. and A. O. Holcombe (2002). "Causality and the perception of time." Trends in cognitive sciences **6**(8): 323-325. doi: DOI: https://doi.org/10.1016/S1364-6613(02)01945-9.

Ebert, J. P. and D. M. Wegner (2010). Time warp: Authorship shapes the perceived timing of actions and events. Consciousness and cognition. **19:** 481-489. doi: http://dx.doi.org/10.1016/j.concog.2009.10.002.

https://doi.org/10.1016/j.concog.2009.10.002.

Ehrlichman, H. and L. Bastone (1992). Olfaction and emotion. Science of olfaction, Springer**:** 410-438. doi: https://doi.org/10.1007/978-1-4612-2836-3_15.

Elish, M. C. (2019). "Moral crumple zones: Cautionary tales in human-robot interaction." Engaging Science, Technology, and Society **5**: 40-60. doi: https://doi.org/10.17351/ests2019.260 .

Ernst, M. O. and M. S. Banks (2002). "Humans integrate visual and haptic information in a statistically optimal fashion." Nature **415**(6870): 429-433. doi: https://doi.org/10.1038/415429a.

Ernst, M. O. and H. H. Bülthoff (2004). "Merging the senses into a robust percept." Trends in cognitive sciences **8**(4): 162-169. doi: https://doi.org/10.1016/j.tics.2004.02.002.

Faul, F., E. Erdfelder, A.-G. Lang and A. Buchner (2007). "G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences." Behavior research methods **39**(2): 175-191. doi: DOI: https://doi.org/10.3758/BF03193146.

Faulhaber, A. K., A. Dittmer, F. Blind, M. A. Wächter, S. Timm, L. R. Sütfeld, A. Stephan, G. Pipa and P. König (2019). "Human decisions in moral dilemmas are largely described by utilitarianism: Virtual car driving study provides guidelines for autonomous driving vehicles." Science and engineering ethics **25**(2): 399-418. doi: https://doi.org/10.1007/s11948-018-0020-x.

Ferdenzi, C., J. Poncelet, C. Rouby and M. Bensafi (2014). "Repeated exposure to odors induces affective habituation of perception and sniffing." Frontiers in behavioral neuroscience **8**: 119. doi: https://doi.org/10.3389/fnbeh.2014.00119.

Ferdenzi, C., S. C. Roberts, A. Schirmer, S. Delplanque, S. Cekic, C. Porcherot, I. Cayeux, D. Sander and D. Grandjean (2013). "Variability of affective responses to odors: culture, gender, and olfactory knowledge." Chemical Senses **38**(2): 175-186. doi: https://doi.org/10.1093/chemse/bjs083.

Fontaine, J. R., K. R. Scherer, E. B. Roesch and P. C. Ellsworth (2007). "The world of emotions is not two-dimensional." Psychological science **18**(12): 1050-1057. doi: https://doi.org/10.1111/j.1467-9280.2007.02024.x.

Franklin, S., B. J. Baars, U. Ramamurthy and M. Ventura (2005). "The role of consciousness in memory." Brains, Minds & Media **1**. http://www.brains-minds-media.org/

Freeman, E., S. Brewster and V. Lantz (2016). Do That, There: An Interaction Technique for Addressing In-Air Gesture Systems. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems. , ACM**:** 2319-2331. doi: http://dx.doi.org/10.1145/2858036.2858308.

Frith, C. D. (1992). The cognitive neuropsychology of schizophrenia, Psychology press.

Frith, C. D., S.-J. Blakemore and D. M. Wolpert (2000). "Abnormalities in the awareness and control of action." Phil. Trans. R. Soc. Lond. B **355**(1404): 1771-1788. doi: https://doi.org/10.1098/rstb.2000.0734.

Garaizar, P., M. A. Vadillo, D. López-de-Ipiña and H. Matute (2014). Measuring software timing errors in the presentation of visual stimuli in cognitive neuroscience experiments. PloS one. **9:** e85108. doi: http://dx.doi.org/10.1371/journal.pone.0085108.

Gatti, E., E. Calzolari, E. Maggioni and M. Obrist (2018). "Emotional ratings and skin conductance response to visual, auditory and haptic stimuli." Scientific data **5**: 180120. doi: https://doi.org/10.1038/sdata.2018.120.

Geffen, G., J. Bradshaw and N. Nettleton (1973). "Attention and hemispheric differences in reaction time during simultaneous audio-visual tasks." The Quarterly journal of experimental psychology **25**(3): 404-412. doi: DOI: http://dx.doi.org/10.1080/14640747308400362.

Georgieff, N. and M. Jeannerod (1998). Beyond consciousness of external reality: a “who” system for consciousness of action and self-consciousness. Consciousness and cognition. **7:** 465-477. doi: http://dx.doi.org/10.1006/ccog.1998.0367.

Gescheider, G. A., J. H. Wright and R. T. Verrillo (2010). Information-processing channels in the tactile sensory system: A psychophysical and physiological analysis, Psychology Press**:** 136.

Ghinea, G. and O. Ademoye (2012). "The sweet smell of success: Enhancing multimedia applications with olfaction." ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM) **8**(1): 2. doi: https://doi.org/10.1145/2663204.2663269.

Ghinea, G. and O. A. Ademoye (2011). "Olfaction-enhanced multimedia: perspectives and challenges." Multimedia Tools and Applications **55**(3): 601-626. doi: https://doi.org/10.1007/s11042-010-0581-4.

Golod, I., F. Heidrich, C. Möllering and M. Ziefle (2013). Design principles of hand gesture interfaces for microinteractions. Proceedings of the 6th International Conference on Designing Pleasurable Products and Interfaces, ACM**:** 11-20. doi: http://dx.doi.org/10.1145/2513506.2513508.

Gonzalez-Franco, M. and J. Lanier (2017). "Model of Illusions and Virtual Reality." Frontiers in psychology **8**. doi: DOI: https://doi.org/10.3389/fpsyg.2017.01125.

Greenberg, J., T. Pyszczynski, J. Burling and K. Tibbs (1992). "Depression, self-focused attention, and the self-serving attributional bias." Personality and Individual Differences **13**(9): 959-965. doi: https://doi.org/10.1016/0191-8869(92)90129-D.

Gupta, S., D. Morris, S. N. Patel and D. Tan (2013). Airwave: Non-contact haptic feedback using air vortex rings. Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing, ACM**:** 419-428. doi: http://dx.doi.org/10.1145/2493432.2493463.

Haggard, P. (2017). "Sense of agency in the human brain." Nature reviews neuroscience **18**(4): 196. doi: https://doi.org/10.1038/nrn.2017.14.

Haggard, P., S. Clark and J. Kalogeras (2002). "Voluntary action and conscious awareness." Nature neuroscience **5**(4): 382-385. doi: DOI: https://dx.doi.org/10.1038/nn827.

Haggard, P. and M. Tsakiris (2009). The experience of agency feelings, judgments, and responsibility. Current Directions in Psychological Science. **18:** 242-246. doi: https://doi.org/10.1111/j.1467-8721.2009.01644.x.

Hamilton-Fletcher, G., M. Obrist, P. Watten, M. Mengucci and J. Ward (2016). I always wanted to see the night sky: blind user preferences for Sensory Substitution Devices. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM. doi: http://dx.doi.org/10.1145/2858036.2858241.

Harrison, C., D. Tan and D. Morris (2010). Skinput: appropriating the body as an input surface. Proceedings of the SIGCHI conference on human factors in computing systems, ACM. doi: DOI: https://dx.doi.org/10.1145/1753326.1753394.

Harrison, C., D. Tan and D. Morris (2011). "Skinput: appropriating the skin as an interactive canvas." Communications of the ACM **54**(8): 111-118. doi: https://doi.org/10.1145/1978542.1978564.

Hartson, R. and P. S. Pyla (2012). The UX Book: Process and guidelines for ensuring a quality user experience, Elsevier.

Hengstler, M., E. Enkel and S. Duelli (2016). "Applied artificial intelligence and trust—The case of autonomous vehicles and medical assistance devices." Technological Forecasting and Social Change **105**: 105-120. doi: https://doi.org/10.1016/j.techfore.2015.12.014.

Herz, R. S. and G. C. Cupchik (1995). "The emotional distinctiveness of odor-evoked memories." Chemical Senses **20**(5): 517-528. doi: https://doi.org/10.1093/chemse/20.5.517.

Hongratanaworakit, T. (2004). "Physiological effects in aromatherapy." Songklanakarin J Sci Technol **26**(1): 117-125.

Hornbæk, K. and A. Oulasvirta (2017). What Is Interaction? Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems. Denver, Colorado, USA, ACM**:** 5040-5052. doi: https://doi.org/10.1145/3025453.3025765.

Hume, D. and T. L. Beauchamp (2000). An enquiry concerning human understanding: A critical edition, Oxford University Press.

Inoue, K., Y. Takeda and M. Kimura (2017). "Sense of agency in continuous action: Assistance-induced performance improvement is self-attributed even with knowledge of assistance." Consciousness and cognition **48**: 246-252. doi: https://doi.org/10.1016/j.concog.2016.12.003.

Johansen, K. (2008). "Perfumed textiles." Textile Society of America Symposium Proceedings.

Johansson, P., L. Hall, S. Sikström and A. Olsson (2005). "Failure to detect mismatches between intention and outcome in a simple decision task." Science **310**(5745): 116-119. doi: DOI: https://dx.doi.org/10.1126/science.1111709.

Johansson, R. S. and Å. B. Vallbo (1979). "Tactile sensibility in the human hand: relative and absolute densities of four types of mechanoreceptive units in glabrous skin." The Journal of physiology **286**(1): 283-300. doi: DOI: https://dx.doi.org/10.1113/jphysiol.1979.sp012619.

Johnson, K. O. and J. R. Phillips (1981). "Tactile spatial resolution. I. Two-point discrimination, gap detection, grating resolution, and letter recognition." Journal of neurophysiology **46**(6): 1177-1192. URL: http://jn.physiology.org/content/46/6/1177

Kaye, J. J. (2004). "Making Scents: aromatic output for HCI." interactions **11**(1): 48-61. doi: https://doi.org/10.1145/962342.964333.

Keller, A. (2011). "Attention and olfactory consciousness." Frontiers in psychology **2**: 380. doi: https://doi.org/10.3389/fpsyg.2011.00380.

Kendall, M. and A. Stuart (1979). "Estimation: maximum likelihood." The advanced theory of statistics **2**: 38-81.

Khalighinejad, N. and P. Haggard (2015). Modulating human sense of agency with non-invasive brain stimulation. Cortex. **69:** 93-103. doi: http://dx.doi.org/10.1016/j.cortex.2015.04.015.

Khalighinejad, N. and P. Haggard (2016). "Extending experiences of voluntary action by association." Proceedings of the National Academy of Sciences **113**(31): 8867-8872. doi: DOI: https://dx.doi.org/10.1073/pnas.1521223113.

Kilteni, K. and H. H. Ehrsson (2017). "Body ownership determines the attenuation of self-generated tactile sensations." Proceedings of the National Academy of Sciences: 201703347.

Kilteni, K. and H. H. Ehrsson (2017). "Body ownership determines the attenuation of self-generated tactile sensations." Proceedings of the National Academy of Sciences **114**(31): 8426-8431. doi: https://doi.org/10.1073/pnas.1703347114.

Kilteni, K., J.-M. Normand, M. V. Sanchez-Vives and M. Slater (2012). "Extending body space in immersive virtual reality: a very long arm illusion." PloS one **7**(7): e40867.

Kokkinara, E., K. Kilteni, K. J. Blom and M. Slater (2016). "First person perspective of seated participants over a walking virtual body leads to illusory agency over the walking." Scientific reports **6**: 28879.

Kolasinski, E. M. (1995). Simulator sickness in virtual environments, US Army Research Institute for the Behavioral and Social Sciences.

Kolich, M. (2013). In-vehicle smell notification system, Google Patents.

Komori, T., R. Fujiwara, M. Tanida and J. Nomura (1995). "Potential antidepressant effects of lemon odor in rats." European Neuropsychopharmacology **5**(4): 477-480. doi: https://doi.org/10.1016/0924-977X(95)80007-O.

Kong, G., K. He and K. Wei (2017). "Sensorimotor experience in virtual reality enhances sense of agency associated with an avatar." Consciousness and cognition **52**: 115-124. doi: DOI: https://doi.org/10.1016/j.concog.2017.04.018.

Kortum, P. (2008). HCI beyond the GUI: Design for haptic, speech, olfactory, and other nontraditional interfaces, Elsevier.

Lakens, D. (2013). "Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs." Frontiers in Psychology **4**: 863. doi: https://doi.org/10.3389/fpsyg.2013.00863.

Lakens, D. (2013). "Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs." Frontiers in psychology **4**. doi: DOI: https://doi.org/10.3389/fpsyg.2013.00863.

Lang, P. J. (2005). "International affective picture system (IAPS): Affective ratings of pictures and instruction manual." Technical report. http://csea.phhp.ufl.edu/media.html

Le Goff, K., A. Rey, P. Haggard, O. Oullier and B. Berberian (2018). "Agency modulates interactions with automation technologies." Ergonomics **61**(9): 1282-1297. doi: https://doi.org/10.1080/00140139.2018.1468493.

Lefcourt, H. M. (1991). Locus of control, Academic Press. doi: https://doi.org/10.1016/B978-0-12-590241-0.50013-7.

Li, S., J. Chen, M. Li, J. Lin and G. Wang (2017). ColorOdor: Odor Broadens The Color Identification of The Blind. Proceedings of the 2017 CHI Conference Extended Abstracts on Human Factors in Computing Systems, ACM. doi: http://dx.doi.org/10.1145/3027063.3053186.

Libet, B. (1999). "Do we have free will?" Journal of consciousness studies **6**(8-9): 47-57. URL: http://www.ingentaconnect.com/content/imp/jcs/1999/00000006/F0020008/966

Libet, B., C. A. Gleason, E. W. Wright and D. K. Pearl (1983). "Time of conscious intention to act in relation to onset of cerebral activity (readiness-potential) the unconscious initiation of a freely voluntary act." Brain **106**(3): 623-642.

Lien, J., N. Gillian, M. E. Karagozler, P. Amihood, C. Schwesig, E. Olson, H. Raja and I. Poupyrev (2016). Soli: ubiquitous gesture sensing with millimeter wave radar. ACM Transactions on Graphics (TOG). **35:** 142. doi: http://dx.doi.org/10.1145/2897824.2925953.

Limerick, H., D. Coyle and J. W. Moore (2015). "The experience of agency in human-computer interactions: a review." Sense Agency Examining Aware. Act. Self. doi: DOI: https://doi.org/10.3389/fnhum.2014.00643.

Limerick, H., J. W. Moore and D. Coyle (2015). Empirical evidence for a diminished sense of agency in speech interfaces. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM. doi: DOI: https://dx.doi.org/10.1145/2702123.2702379.

Liu, M., M. Nancel and D. Vogel (2015). Gunslinger: Subtle Arms-down Mid-air Interaction. Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology, ACM**:** 63-71. doi: http://dx.doi.org/10.1145/2807442.2807489.

Lynn, M. T., P. S. Muhle-Karbe, H. Aarts and M. Brass (2014). "Priming determinist beliefs diminishes implicit (but not explicit) components of self-agency." Frontiers in psychology **5**. doi: https://dx.doi.org/10.3389/fpsyg.2014.01483.

Maeda, T., M. Kato, T. Muramatsu, S. Iwashita, M. Mimura and H. Kashima (2012). Aberrant sense of agency in patients with schizophrenia: Forward and backward over-attribution of temporal causality during intentional action. Psychiatry Research. **198:** 1-6. doi: http://dx.doi.org/10.1016/j.psychres.2011.10.021.

Maggioni, E., R. Cobden, D. Dmitrenko and M. Obrist (2018). Smell-O-Message: Integration of Olfactory Notifications into a Messaging Application to Improve Users' Performance. 2018 International Conference on Multimodal Interaction (ICMI '18), Boulder, CO, USA, ACM, New York, NY, USA. doi: https://doi.org/10.1145/3242969.3242975

Makino, Y., Y. Furuyama, S. Inoue and H. Shinoda (2016). HaptoClone (Haptic-Optical Clone) for Mutual Tele-Environment by Real-time 3D Image Transfer with Midair Force Feedback. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM**:** 1980-1990. doi: http://dx.doi.org/10.1145/2858036.2858481.

Maples-Keller, J. L., C. Yasinski, N. Manjin and B. O. Rothbaum (2017). "Virtual reality-enhanced extinction of phobias and post-traumatic stress." Neurotherapeutics **14**(3): 554-563. doi: https://doi.org/10.1007/s13311-017-0534-y.

Markussen, A., M. R. Jakobsen and K. Hornbæk (2014). Vulture: a mid-air word-gesture keyboard. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM**:** 1073-1082. doi: http://dx.doi.org/10.1145/2556288.2556964.

Matsukura, H., T. Yoneda and H. Ishida (2013). "Smelling screen: development and evaluation of an olfactory display system for presenting a virtual odor source." IEEE transactions on visualization and computer graphics **19**(4): 606-615. doi: https://doi.org/10.1109/TVCG.2013.40.

McEneaney, J. E. (2013). "Agency effects in human–computer interaction." International Journal of Human-Computer Interaction **29**(12): 798-813. doi: http://dx.doi.org/10.1080/10447318.2013.777826.

McIntosh, J., C. McNeill, M. Fraser, F. Kerber, M. Löchtefeld and A. Krüger (2016). EMPress: Practical Hand Gesture Classification with Wrist-Mounted EMG and Pressure Sensing.

Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM**:** 2332-2342. doi: http://dx.doi.org/10.1145/2858036.2858093.
Mehrabian, A. and J. A. Russell (1974). An approach to environmental psychology, the MIT Press. URL: http://psycnet.apa.org/record/1974-22049-000
Mellor, C. S. (1970). First rank symptoms of schizophrenia: I. The frequency in schizophrenics on admission to hospital. II. Differences between individual first rank symptoms. The British Journal of Psychiatry. **117(536):** 15-23. doi: https://doi.org/10.1192S0007125000192116.
Mezulis, A. H., L. Y. Abramson, J. S. Hyde and B. L. Hankin (2004). "Is there a universal positivity bias in attributions? A meta-analytic review of individual, developmental, and cultural differences in the self-serving attributional bias." Psychological bulletin **130**(5): 711. doi: http://dx.doi.org/10.1037/0033-2909.130.5.711.
Miller, M. K. and R. L. Mandryk (2016). Differentiating in-game frustration from at-game frustration using touch pressure. Proceedings of the 2016 ACM on Interactive Surfaces and Spaces, ACM. doi: http://dx.doi.org/10.1145/2992154.2992185.
Mochizuki, A., T. Amada, S. Sawa, T. Takeda, S. Motoyashiki, K. Kohyama, M. Imura and K. Chihara (2004). Fragra: a visual-olfactory VR game. ACM SIGGRAPH 2004 Sketches, ACM. doi: https://doi.org/10.1145/1186223.1186377.
Mok, B., M. Johns, D. Miller and W. Ju (2017). Tunneled in: Drivers with active secondary tasks need more time to transition from automation. Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, ACM. doi: http://dx.doi.org/10.1145/3025453.3025713.
Monnai, Y., K. Hasegawa, M. Fujiwara, K. Yoshino, S. Inoue and H. Shinoda (2014). HaptoMime: mid-air haptic interaction with a floating virtual screen. Proceedings of the 27th annual ACM symposium on User interface software and technology, ACM**:** 663-667. doi: http://dx.doi.org/10.1145/2642918.2647407.
Montano Murillo, R. A., E. Gatti, M. Oliver Segovia, M. Obrist, J. P. Molina Masso and D. Martinez Plasencia (2017). "NaviFields: Relevance fields for adaptive VR navigation." UIST 2017, Quebec City, QC, Canada. doi: DOI: https://doi.org/10.1145/3126594.3126645.
Montano Murillo, R. A., D. Martinez Plasencia and S. Subramanian (2017). "Erg-O: Ergonomic Optimization of Immersive Virtual Environments." UIST 2017, Quebec City, QC, Canada. doi: DOI: https://doi.org/10.1145/3126594.3126605.
Moore, J. and P. Haggard (2008). "Awareness of action: Inference and prediction." Consciousness and cognition **17**(1): 136-144. doi: DOI: https://doi.org/10.1016/j.concog.2006.12.004.
Moore, J. W. (2016). "What is the sense of agency and why does it matter?" Frontiers in psychology **7**: 1272. doi: https://doi.org/10.3389/fpsyg.2016.01272.
Moore, J. W. and P. C. Fletcher (2012). "Sense of agency in health and disease: a review of cue integration approaches." Consciousness and cognition **21**(1): 59-68. doi: https://doi.org/10.1016/j.concog.2011.08.010.
Moore, J. W. and P. Haggard (2010). "Intentional binding and higher order agency experience." Consciousness and cognition **19**(1): 490-491. doi: https://doi.org/10.1016/j.concog.2009.11.007.
Moore, J. W. and S. S. Obhi (2012). "Intentional binding and the sense of agency: a review." Consciousness and cognition **21**(1): 546-561. doi: DOI: https://doi.org/10.1016/j.concog.2011.12.002.
Moore, J. W., D. M. Wegner and P. Haggard (2009). "Modulating the sense of agency with external cues." Consciousness and cognition **18**(4): 1056-1064. doi: https://doi.org/10.1016/j.concog.2009.05.004.
Moretto, G., E. Walsh and P. Haggard (2011). "Experience of agency and sense of responsibility." Consciousness and cognition **20**(4): 1847-1854. doi: DOI: https://doi.org/10.1016/j.concog.2011.08.014.

Motomura, N., A. Sakurai and Y. Yotsuya (2001). "Reduction of mental stress with lavender odorant." Perceptual and motor skills **93**(3): 713-718. doi: https://doi.org/10.2466/pms.2001.93.3.713.

Müller, J., M. Geier, C. Dicke and S. Spors (2014). The boomRoom: mid-air direct interaction with virtual sound sources. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM**:** 247-256. doi: http://dx.doi.org/10.1145/2556288.2557000.

Nakaizumi, F., H. Noma, K. Hosaka and Y. Yanagida (2006). SpotScents: A novel method of natural scent delivery using multiple scent projectors. Virtual Reality Conference, 2006, IEEE. doi: https://doi.org/10.1109/VR.2006.122.

Nakamoto, T., S. Otaguro, M. Kinoshita, M. Nagahama, K. Ohinishi and T. Ishida (2008). "Cooking up an interactive olfactory game display." IEEE Computer Graphics and Applications **28**(1). doi: https://doi.org/10.1109/MCG.2008.3.

Nandakumar, R., V. Iyer, D. Tan and S. Gollakota (2016). FingerIO: Using Active Sonar for Fine-Grained Finger Tracking. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM**:** 1515-1525. doi: http://dx.doi.org/10.1145/2858036.2858580.

Narumi, T., S. Nishizaka, T. Kajinami, T. Tanikawa and M. Hirose (2011). Augmented reality flavors: gustatory display based on edible marker and cross-modal interaction. Proceedings of the SIGCHI conference on human factors in computing systems, ACM. doi: https://doi.org/10.1145/1978942.1978957.

Norman, D. A. (1986). "Cognitive engineering." User centered system design **31**: 61.

Normand, J.-M., E. Giannopoulos, B. Spanlang and M. Slater (2011). "Multisensory stimulation can induce an illusion of larger belly size in immersive virtual reality." PloS one **6**(1): e16128.

Nuwer, R. (2013). Armband adds a twitch to gesture control. New Scientist. **217:** 21. doi: http://dx.doi.org/10.1016/S0262-4079(13)60542-4.

O'Hara, K., G. Gonzalez, A. Sellen, G. Penney, A. Varnavas, H. Mentis, A. Criminisi, R. Corish, M. Rouncefield and N. Dastur (2014). Touchless interaction in surgery. Communications of the ACM. **57:** 70-77. doi: http://dx.doi.org/10.1145/2541883.2541899

O'Brien, H. L., P. Cairns and M. Hall (2018). "A practical approach to measuring user engagement with the refined user engagement scale (UES) and new UES short form." International Journal of Human-Computer Studies **112**: 28-39. doi: https://doi.org/10.1016/j.ijhcs.2018.01.004.

Obhi, S. and P. Haggard (2004). "Free Will and Free Won't Motor activity in the brain precedes our awareness of the intention to move, so how is it that we perceive control?" Am. Sci **92**: 358-365.

Obhi, S. S. and P. Hall (2011). Sense of agency and intentional binding in joint action. Experimental brain research. **211:** 655-662. doi: http://dx.doi.org/10.1007/s00221-011-2675-2.

Obrist, M., E. Gatti, E. Maggioni, C. T. Vi and C. Velasco (2017). "Multisensory experiences in HCI." IEEE MultiMedia **24**(2): 9-13. doi: https://doi.org/10.1109/MMUL.2017.33.

Obrist, M., N. Ranasinghe and C. Spence (2017). "Special issue: Multisensory human–computer interaction." doi: https://doi.org/10.1016/j.ijhcs.2017.06.002.

Obrist, M., A. N. Tuch and K. Hornbaek (2014). Opportunities for odor: experiences with smell and implications for technology. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM. doi: http://dx.doi.org/10.1145/2556288.2557008.

Olofsson, J. K. (2014). "Time to smell: a cascade model of human olfactory perception based on response-time (RT) measurement." Frontiers in psychology **5**: 33. doi: https://doi.org/10.3389/fpsyg.2014.00033.

Peck, T. C., S. Seinfeld, S. M. Aglioti and M. Slater (2013). "Putting yourself in the skin of a black avatar reduces implicit racial bias." Consciousness and cognition **22**(3): 779-787.

Pellegrino, R., C. Sinding, R. De Wijk and T. Hummel (2017). "Habituation and adaptation to odors in humans." Physiology & behavior **177**: 13-19. doi: https://doi.org/10.1016/j.physbeh.2017.04.006.

Plush Folly. Available from: https://plushfolly.com/.
Pockett, S. and A. Miller (2007). "The rotating spot method of timing subjective events." Consciousness and cognition **16**(2): 241-254. doi: https://doi.org/10.1016/j.concog.2006.09.002.
Porter, J., B. Craven, R. M. Khan, S.-J. Chang, I. Kang, B. Judkewitz, J. Volpe, G. Settles and N. Sobel (2007). "Mechanisms of scent-tracking in humans." Nature neuroscience **10**(1): 27. doi: http://dx.doi.org/10.1038/nn1819.
Ramic-Brkic, B. and A. Chalmers (2014). "Olfactory adaptation in virtual environments." ACM Transactions on Applied Perception (TAP) **11**(2): 6. doi: https://doi.org/10.1145/2617917.
Ranasinghe, N., K. Karunanayaka, A. D. Cheok, O. N. N. Fernando, H. Nii and P. Gopalakrishnakone (2011). Digital taste and smell communication. Proceedings of the 6th international conference on body area networks, ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering).
Rinaldi, L., E. Maggioni, N. Olivero, A. Maravita and L. Girelli (2018). "Smelling the space around us: Odor pleasantness shifts visuospatial attention in humans." Emotion **18**(7): 971. doi: http://dx.doi.org/10.1037/emo0000335.
Russell, J. A. and A. Mehrabian (1977). "Evidence for a three-factor theory of emotions." Journal of research in Personality **11**(3): 273-294. doi: DOI: https://doi.org/10.1016/0092-6566(77)90037-X.
Saffer, D. (2008). Designing gestural interfaces: Touchscreens and interactive devices, " O'Reilly Media, Inc."**:** 272.
Sauter, D. A., F. Eisner, A. J. Calder and S. K. Scott (2010). "Perceptual cues in nonverbal vocal expressions of emotion." Quarterly Journal of Experimental Psychology **63**(11): 2251-2272. doi: https://doi.org/10.1080/17470211003721642.
Sbrollini, M. C. (1987). "Olfactory delights." Journal of Chemical Education **64**(9): 799. doi: https://doi.org/10.1021/ed064p799.
Schmid, S., D. A. Wilson and C. H. Rankin (2014). "Habituation mechanisms and their importance for cognitive function." Frontiers in integrative neuroscience **8**. doi: DOI: https://dx.doi.org/10.3389/fnint.2014.00097.
Schultze-Kraft, M., D. Birman, M. Rusconi, C. Allefeld, K. Görgen, S. Dähne, B. Blankertz and J.-D. Haynes (2016). "The point of no return in vetoing self-initiated movements." Proceedings of the National Academy of Sciences **113**(4): 1080-1085. doi: DOI: https://dx.doi.org/10.1073/pnas.1513569112.
Seah, S. A., D. Martinez Plasencia, P. D. Bennett, A. Karnik, V. S. Otrocol, J. Knibbe, A. Cockburn and S. Subramanian (2014). SensaBubble: a chrono-sensory mid-air display of sight and smell. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM. doi: http://dx.doi.org/10.1145/2556288.2557087.
Serrano, B., R. M. Baños and C. Botella (2016). "Virtual reality and stimulation of touch and smell for inducing relaxation: A randomized controlled trial." Computers in human behavior **55**: 1-8. doi: https://doi.org/10.1016/j.chb.2015.08.007.
Shepherd, G. M. (2004). "The Human Sense of Smell: Are We Better Than We Think?" PLOS Biology **2**(5): e146. doi: https://doi.org/10.1371/journal.pbio.0020146.
Shneiderman, B. (1980). "Software psychology: Human factors in computer and information systems."
Shneiderman, B. (2004). "Designing for fun: how can we design user interfaces to be more fun?" interactions **11**(5): 48-50. doi: https://doi.org/10.1145/1015530.1015552.
Shneiderman, B. (2005). "Shneiderman's eight golden rules of interface design." Retrieved July **25**: 2009. doi: https://dx.doi.org/10.1145/1015530.1015552.
Shneiderman, S. B. and C. Plaisant (2005). "Designing the user interface 4 th edition." ed: Pearson Addison Wesley, USA.
Sidarus, N., V. Chambon and P. Haggard (2013). "Priming of actions increases sense of control over unexpected outcomes." Consciousness and cognition **22**(4): 1403-1411. doi: DOI: https://doi.org/10.1016/j.concog.2013.09.008.

Sidarus, N., M. Vuorre and P. Haggard (2017). "Integrating prospective and retrospective cues to the sense of agency: a multi-study investigation." Neuroscience of Consciousness **3**(1). doi: DOI: https://doi.org/10.1093/nc/nix012.

Siek, K. A., Y. Rogers and K. H. Connelly (2005). Fat finger worries: how older and younger users physically interact with PDAs. IFIP Conference on Human-Computer Interaction, Springer. doi: https://doi.org/10.1007/11555261_24.

Smith, B. C. (2015). The chemical senses. The Oxford handbook of philosophy of perception. doi: https://doi.org/10.1093/oxfordhb/9780199600472.013.045.

Sodhi, R., I. Poupyrev, M. Glisson and A. Israr (2013). AIREAL: interactive tactile experiences in free air. ACM Transactions on Graphics (TOG). **32:** 134. doi: http://dx.doi.org/10.1145/2461912.2462007.

Soon, C. S., M. Brass, H.-J. Heinze and J.-D. Haynes (2008). "Unconscious determinants of free decisions in the human brain." Nature neuroscience **11**(5): 543-545. doi: DOI: https://dx.doi.org/10.1038/nn.2112.

Soudry, Y., C. Lemogne, D. Malinvaud, S.-M. Consoli and P. Bonfils (2011). "Olfactory system and emotion: common substrates." European annals of otorhinolaryngology, head and neck diseases **128**(1): 18-23. doi: https://doi.org/10.1016/j.anorl.2010.09.007.

Sridhar, S., A. Markussen, A. Oulasvirta, C. Theobalt and S. Boring (2017). WatchSense: On- and Above-Skin Input Sensing through a Wearable Depth Sensor. Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, ACM. doi: DOI: https://dx.doi.org/10.1145/3025453.3026005.

Stenner, M.-P., M. Bauer, N. Sidarus, H.-J. Heinze, P. Haggard and R. J. Dolan (2014). "Subliminal action priming modulates the perceived intensity of sensory action consequences." Cognition **130**(2): 227-235. doi: DOI: https://doi.org/10.1016/j.cognition.2013.11.008.

Stewart, N. (2006). Millisecond accuracy video display using OpenGL under Linux. Behavior research methods. **38:** 142-145. doi: http://dx.doi.org/10.3758/BF03192759.

Strother, L., K. A. House and S. S. Obhi (2010). "Subjective agency and awareness of shared actions." Consciousness and cognition **19**(1): 12-20. doi: DOI: https://doi.org/10.1016/j.concog.2009.12.007.

Synofzik, M., G. Vosgerau and A. Newen (2008). "Beyond the comparator model: a multifactorial two-step account of agency." Consciousness and cognition **17**(1): 219-239. doi: DOI: https://doi.org/10.1016/j.concog.2007.03.010.

Synofzik, M., G. Vosgerau and M. Voss (2013). "The experience of agency: an interplay between prediction and postdiction." Frontiers in psychology **4**. doi: https://dx.doi.org/10.1422/77217.

Takahata, K., H. Takahashi, T. Maeda, S. Umeda, T. Suhara, M. Mimura and M. Kato (2012). "It’s not my fault: Postdictive modulation of intentional binding by monetary gains and losses." PloS one **7**(12): e53421. doi: https://doi.org/10.1371/journal.pone.0053421

Taylor, J., L. Bordeaux, T. Cashman, B. Corish, C. Keskin, T. Sharp, E. Soto, D. Sweeney, J. Valentin and B. Luff (2016). Efficient and precise interactive hand tracking through joint, continuous optimization of pose and correspondences. ACM Transactions on Graphics (TOG). **35:** 143. doi: http://dx.doi.org/10.1145/2897824.2925965.

Tham, W. W., R. J. Stevenson and L. A. Miller (2009). "The functional role of the medio dorsal thalamic nucleus in olfaction." Brain research reviews **62**(1): 109-126. doi: https://doi.org/10.1016/j.brainresrev.2009.09.007.

Tregillus, S., M. Al Zayer and E. Folmer (2017). Handsfree Omnidirectional VR Navigation using Head Tilt. Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, ACM. doi: DOI: https://dx.doi.org/10.1145/3025453.3025521.

Uijong, J., J. Kang and C. Wallraven (2019). "You or me? Personality traits predict sacrificial decisions in an accident situation." IEEE transactions on visualization and computer graphics **25**(5): 1898-1907. doi: https://doi.org/10.1109/TVCG.2019.2899227.

Usrey, W. M. and H. J. Alitto (2015). "Visual Functions of the Thalamus." Annual Review of Vision Science **1**(1): 351-371. doi: https://doi.org/10.1146/annurev-vision-082114-035920.

Van De Grind, W. (2002). Physical, neural, and mental timing, Elsevier. doi: DOI: https://doi.org/10.1006/ccog.2002.0560.
Van Toller, C., M. Kirk-Smith, N. Wood, J. Lombard and G. H. Dodd (1983). "Skin conductance and subjective assessments associated with the odour of 5-α-androstan-3-one." Biological Psychology **16**(1-2): 85-107. doi: https://doi.org/10.1016/0301-0511(83)90056-X.
Vernet-Maury, E., O. Alaoui-Ismaı̈li, A. Dittmar, G. Delhomme and J. Chanel (1999). "Basic emotions induced by odorants: a new approach based on autonomic pattern results." Journal of the autonomic nervous system **75**(2): 176-183. doi: https://doi.org/10.1016/S0165-1838(98)00168-4.
Vi, C. T., D. Ablart, D. Arthur and M. Obrist (2017). Gustatory interface: the challenges of 'how'to stimulate the sense of taste. Proceedings of 2nd ACM SIGCHI International Workshop on Multisensory Approaches to Human-Food Interaction (MHFI'17), ACM. doi: https://doi.org/10.1145/3141788.3141794.
Vi, C. T., A. Marzo, D. Ablart, G. Memoli, S. Subramanian, B. Drinkwater and M. Obrist (2017). TastyFloats: a contactless food delivery system. Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces, ACM. doi: https://doi.org/10.1145/3132272.3134123.
Wang, S., J. Xu, W. Wang, G.-J. N. Wang, R. Rastak, F. Molina-Lopez, J. W. Chung, S. Niu, V. R. Feig and J. Lopez (2018). "Skin electronics from scalable fabrication of an intrinsically stretchable transistor array." Nature **555**(7694): 83. doi: https://doi.org/10.1038/nature25494.
Warrenburg, S. (2005). "Effects of fragrance on emotions: moods and physiology." Chemical Senses **30**(suppl_1): i248-i249. doi: https://doi.org/10.1093/chemse/bjh208.
Weber, S. T. and E. Heuberger (2008). "The impact of natural odors on affective states in humans." Chemical Senses **33**(5): 441-447. doi: https://doi.org/10.1093/chemse/bjn011.
Wegner, D. (2002). The illusion of conscious will. Cambridge: A Bradford Book, The MIT Press.
Wegner, D. M. (2003). The mind's best trick: how we experience conscious will. Trends in cognitive sciences. **7:** 65-69. doi: http://dx.doi.org/10.1016/S1364-6613(03)00002-0.
Wegner, D. M. (2003). "The mind's best trick: how we experience conscious will." Trends in cognitive sciences **7**(2): 65-69. doi: https://doi.org/10.1016/S1364-6613(03)00002-0.
Wegner, D. M., B. Sparrow and L. Winerman (2004). Vicarious agency: experiencing control over the movements of others. Journal of personality and social psychology. **86:** 838. doi: http://dx.doi.org/10.1037/0022-3514.86.6.838.
Wegner, D. M. and T. Wheatley (1999). "Apparent mental causation: Sources of the experience of will." American psychologist **54**(7): 480. doi: http://dx.doi.org/10.1037/0003-066X.54.7.480.
Weiskrantz, L., J. Elliott and C. Darlington (1971). "Preliminary observations on tickling oneself." Nature **230**(5296): 598. doi: https://doi.org/10.1038/230598a0.
Wen, W., A. Yamashita and H. Asama (2015). "The sense of agency during continuous action: performance is more important than action-feedback association." PloS one **10**(4): e0125226. doi: https://doi.org/10.1371/journal.pone.0125226.
Wenke, D., S. M. Fleming and P. Haggard (2010). "Subliminal priming of actions influences sense of control over effects of action." Cognition **115**(1): 26-38. doi: DOI: https://doi.org/10.1016/j.cognition.2009.10.016.
Wigdor, D. and D. Wixon (2011). Brave NUI world: designing natural user interfaces for touch and gesture, Elsevier. **36**. doi: http://dx.doi.org/10.1145/2047414.2047439.
Williamson, J., R. Murray-Smith, B. Blankertz, M. Krauledat and K.-R. Müller (2009). "Designing for uncertain, asymmetric control: Interaction design for brain–computer interfaces." International Journal of Human-Computer Studies **67**(10): 827-841. doi: https://doi.org/10.1016/j.ijhcs.2009.05.009.
Wolpert, D. M. and J. R. Flanagan (2001). "Motor prediction." Current Biology **11**(18): R729-R732. doi: https://doi.org/10.1016/S0960-9822(01)00432-8.

Wu, W. and S. Rank (2015). Responsive Environmental Diegetic Audio Feedback for Hand Gestures in Audio-Only Games. Proceedings of the 2015 Annual Symposium on Computer-Human Interaction in Play, ACM**:** 739-744. doi: http://dx.doi.org/10.1145/2793107.2810336.

Wu, W. and S. Rank (2015). Spatial Audio Feedback for Hand Gestures in Games. Proceedings of the 3rd ACM Symposium on Spatial User Interaction, ACM**:** 135-135. doi: http://dx.doi.org/10.1145/2788940.2794363.

Xuan, L., G. Daisong, Z. Moli, Z. Jingya, L. Xingtong and L. Siqi (2019). Comparison on user experience of mid-air gesture interaction and traditional remotes control. Proceedings of the Seventh International Symposium of Chinese CHI. doi: https://doi.org/10.1145/3332169.3333570.

Yanagida, Y., S. Kawato, H. Noma, A. Tomono and N. Tesutani (2004). Projection based olfactory display with nose tracking. Virtual Reality, 2004. Proceedings. IEEE, IEEE. doi: https://doi.org/10.1109/VR.2004.1310054.

Yoshida, M., C. Kato, M. Kawasumi, H. Yamasaki, S. Yamamoto, T. Nakano and M. Yamada (2011). Study on Stimulation Effects for Driver Based on Fragrance Presentation. MVA. http://www.mva-org.jp/Proceedings/2011CD/papers/09-26.pdf

Yoshie, M. and P. Haggard (2013). "Negative emotional outcomes attenuate sense of agency over voluntary actions." Current Biology **23**(20): 2028-2032. doi: https://doi.org/10.1016/j.cub.2013.08.034.

Yoshie, M. and P. Haggard (2017). "Effects of emotional valence on sense of agency require a predictive model." Scientific reports **7**(1): 8733. doi: https://doi.org/10.1038/s41598-017-08803-3.

Zald, D. H. and J. V. Pardo (1997). "Emotion, olfaction, and the human amygdala: amygdala activation during aversive olfactory stimulation." Proceedings of the National Academy of Sciences **94**(8): 4119-4124. http://www.pnas.org/content/94/8/4119

Zarzo, M. (2008). "Psychologic dimensions in the perception of everyday odors: pleasantness and edibility." Journal of Sensory Studies **23**(3): 354-376. doi: https://doi.org/10.1111/j.1745-459X.2008.00160.x.

Zhang, E. Y. and A. D. Cheok (2016). A networked device for reproducing multisensory kissing. Proceedings of the 2016 workshop on Multimodal Virtual and Augmented Reality, ACM. doi: http://dx.doi.org/10.1145/3001959.3001962.

Zhang, Y., J. Zhou, G. Laput and C. Harrison (2016). Skintrack: Using the body as an electrical waveguide for continuous finger tracking on the skin. Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM. doi: DOI: https://dx.doi.org/10.1145/2858036.2858082.

Zhang, Z. (2012). Microsoft kinect sensor and its effect. IEEE MultiMedia. **19:** 4-10. doi: http://dx.doi.org/10.1109/MMUL.2012.24.