The Inter Stimuli- and Visually-Dependent Effects of Vibrotactile Stimuli on Saltation in Virtual Reality

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Title: The Inter Stimuli- and Visually-Dependent Effects of Vibrotactile Stimuli on Saltation in Virtual Reality

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Abstract: How visual feedback affects the cutaneous rabbit illusion is essential for this project, as the visual sense plays a dominant role in interpreting the immediate environment, and might therefore influence the behavior of saltation.

Due to the required diversity of feedback for virtual applications, it is also of interest to test if the cutaneous rabbit illusion will occur on a curvilinear path of points, in addition to the linear path that research has exclusively focused on so far.

Thus, the project explores how visual feedback in a virtual reality simulation affects the perception of saltation from linear and curvilinear vibrotactile stimuli.

To test this, participants were put in a virtual environment through head-mounted display. A virtual avatar was part of the virtual scene, to represent the participants' physical body. A tactile display consisting of mini motor discs placed in a consecutive array was put on the left arm of the participant, and would provide vibrotactile feedback during the virtual simulation. Inside the virtual environment, the participants would see a ball move up their arm, while feeling taps from the vibrations simultaneously.

The test was a between-group design, where a group would experience either a linear or a curvilinear array of vibrotactile stimuli. Participants would try a 2 by 4 test design within each group, consisting of 4 visually-dependent variables of either continuous linear movement, linear movement with jumps between taps, continuous curvilinear movement, or curvilinear movement with jumps between taps. These visual conditions were coupled with 2 vibrotactile-dependent variables of either 5 points-of-stimuli of 3 taps or 3 points of stimuli of 5 taps. The Cuteaneous Rabbit can be transferred successfully to virtual reality, and the visual feedback will enhance the illusion to the point where 3 points of stimuli is almost as compelling as 5 points of stimuli. This means that hardware can effectively be reduced without reducing the illusion. Moreover, while visuals will enhance the cutaneous rabbit illusion, incongruent visual feedback will not break the illusion, but rather modulate the perception of it in terms of its path and distance between taps.

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MOTIVATION

The field of interest for this project is haptic illusions in virtual reality (VR). We wish to explore the possibilities that the sensual system affords haptic illusions in VR, by the interaction across the senses.

Researchers have successfully generated the illusion of saltation of tapping across the skin, emerging from three points of haptic feedback. This haptic illusion is called the cutaneous rabbit illusion. The current state of theory does, however, not include how this illusion might translate to VR.

This has led to the initial problem statement:

1.1 Initial Problem Statement

How will a virtual reality simulation affect the cutaneous rabbit illusion?

2. ANALYSIS

The following chapter will explore the current state of theory regarding haptic illusions, namely the cutaneous rabbit illusion. In continuation thereof, the human cutaneous system will be accounted for, to the extent relevant for the purposes of this project, as this will focus on haptics.

The field of interest is haptics in a VR simulation, and it is therefore relevant to explore concepts such as body ownership and presence. These concepts relate to the experience of a virtual environment, and especially with an illusion like the cutaneous rabbit, where a virtual body most probably will be used.

2.1 Introduction

Though VR is far from a recent construct, there has been a rapid development within the technology in the recent years. The experience of a compelling virtual world is no longer restricted to the confines of research facilities and other wealthy institutions – it is now readily available for everyday consumers and virtual reality enthusiasts as well.

With devices like the Oculus Rift and the HTC Vive, immersion into new worlds has never been more accessible, and the realism of these worlds is fast evolving. Researchers and developers alike constantly take new strides to improve the virtual experiences and make them more believable. Sutherland's discussion of the Ultimate Display seems increasingly like something to aspire to, rather than a mere pipe dream (Sutherland, 1965). In this aspiration, it is relevant to understand how the perceptual system interacts across the senses, to optimize these displays.

In VR applications, the visual and auditory channels are highly saturated, meaning that most of the stimuli is elicited through these channels, and most often the sole focus of any given application. However, stimulating other channels, like the cutaneous system, might make for a more compelling illusion, as multimodal, embodied interaction could make the functionality feel more natural (Maclean & Hayward, 2008). And in the effort to create more immersive experiences, developers have been looking to the haptic hardware to engage users.

In 2014, KOR-FX introduced the haptic gaming vest to give video game players a vibrotactile feedback to first-person shooters games, and letting them feel where bullets have hit (KOR-FX, 2014). Lately, developers have been engaging with full-body suits to deliver detailed, haptic feedback across the entire body; Tesla released its Tesla Suit in 2015 for body tracking and electrotactile feedback, which includes 46 points of feedback distributed over legs, arms and torso (TeslaSuit, 2015); The Hardlight VR Suit, delivering vibrations to the torso and arms through 16 haptic points (Suit, 2017);.

KOR-FX haptic vest

Teslasuit

Hardlight VR Suit

VR suits are good for engaging the user's haptic sense in an effort to immerse them further in the virtual world. However, it seems that the suits are introduced for single-point activation experiences – like being hit by a bullet or an arrow, meaning an isolated event. It has yet to be demonstrated how the haptic wear simulates continuous motion. Moreover, research on requirements of actuator interval to simulate such various tactile experiences, has yet to set a guideline for how tactile feedback is perceived. As the visual and auditory senses have constraints as well as affordances, they are subject to various perceptual illusions. For years, applications have taken advantage of the constraints to create spatial illusions; linear perspective, optic occlusions, relative object-sizes, colours, head-related transfer function, etc., are all used to create spatial depth where there is none.

This begs the question; why not exploit haptic illusions, to create tactile sensations in VR?

In 2004, it was demonstrated that illusions, like the perceptual weight of an object, can be transferred into a virtual environment (Miyazaki, et al., 2010). The size-weight illusion refers to the perceptual phenomenon on estimating weight, based on the size of an object; in a scenario with two virtual boxes of varied sizes, but same weight, the small box will feel heavier than the big box, due to our expectations of a small box weighing less.

Another interesting tactile illusion, is the Cutaneous Rabbit Illusion – a tactile event which leads to the perception of a linear, uniform, and evenly distributed taps across the skin, while the actual tactile stimuli consists of taps unevenly distributed linearly in clusters along the skin (Flach & Haggard, 2006).

The tactile illusion occurs due to the skin's mechanoreceptors that signals the occurrence of haptic stimuli. The density of receptors in the skin, determine the precision of spatial perception from the stimuli. And in the case where any tactile exploration is not possible, and spatial percept is at the mercy of mechano-receptors alone, the ability to localize stimuli is rather limited. The spatial acuity on fingertips will only be able to sense details of 1mm, and in low acuity skin, like the forearm, the resolving detail is down to 1cm (Weinstein, 1968).

On body parts where skin holds low acuity (forearm, legs, etc.), multiple tactors that are placed apart but still within the same receptor field, will fire the same signal, and the observer will experience stimuli from only one location (Weinstein, 1968). Low acuity skin (LAS) only has acuity of 1cm, whereas the fingertips can perceive details down to 1mm (Weinstein, 1968). As such, body parts with low acuity are subject to tactile illusions (Goldreich, 2007)

And this raises an opportunity in the field of tactile feedback in virtual reality.

2.1 The Cutaneous System

This section will describe the human cutaneous system, i.e. the sense of touch, to the extent relevant for this project. The basic functions of the system will be considered both in regard to design choices and state of the theory, and thus, the purpose of this section is to familiarise terms and concepts for those respects. Though the cutaneous system provides a variety of information about the immediate environment, the following will focus solely on the receptors in the skin that respond to the type of stimuli employed for this project, which are the mechanoreceptors.

A sensory receptor is a neuron (in this case, a neuron in the skin), which is sensitive to environmental energy. This energy is changed into electrical signals in the nervous system, to provide the brain information on said environment. These receptors have receptive fields, which are the area of the receptor surface that will affect the firing of that neuron, when stimulated. There are four types of mechanoreceptors in the skin, which are placed respectively in the epidermis (outer layer of the skin) and dermis (inner layer of the skin) (Goldstein, 2007).

Mechanoreceptors are the receptors in the skin which perceive tactile events. Different types of mechanoreceptors have different sizes of receptive fields, where one distinguishes between small or large receptive fields. Mechanoreceptors with small receptive fields are embedded in the epidermis, and the ones with large receptive fields are embedded in the dermis (Wolfe, et al., 2009; Wolfe, et al., 2009).

The mechanoreceptors in the epidermis are respectively Meissner and Merkel, which respond to different properties of tactile stimulus, and they have different structures of firing in response to said tactile stimulus. The Meissner receptor are fast adapting, and fires when the stimulus is first applied, and then only again when the stimulus is removed. The type of perception the Meissner receptor will respond to, is pressure associated with gripping objects. The Merkel corpuscle is slow adapting, and will fire continuously as long as the stimulus is applied, and is sensitive to detecting fine spatial details, like e.g. reading braille (Goldstein, 2007).

The other two types of mechanoreceptors, the Ruffini cylinder and the Pacinian corpuscle, are embedded in the dermis. The Pacinian corpuscle fires when the stimulus is first applied, and only again when the stimulus is removed, and is sensitive to rapid vibrations and detecting fine texture. The Ruffini cylinder fires continuously while the stimulus is applied, and is associated with sensing stretching of the skin (Goldstein, 2007).

The tactile acuity varies throughout the skin. This is both due to the varying density of different mechanoreceptors in the skin, as well as the size of the area on the cortex that represents this particular area of the body. This has been visually represented with a homunculus, where the size of various body parts corresponds to the size of the area of the brain which represents it (see Figure 1). Areas like the palms, soles of the feet, and the lips have high tactile acuity, and are therefore relatively larger than areas like the arms, legs, and back with low tactile acuity (Goldstein, 2007).

Figure 1: The Homunculus representation of the human body's senses

When applying mechanical stimuli like vibrations to the skin, the Pacinian corpuscle will fire, and due to its large receptive fields, there resolving details of the stimuli will be low (Wolfe, et al., 2009). And on body parts where skin holds low acuity (forearm, legs, etc., as seen on Figure 1), multiple points of stimuli that are placed apart but still within the same receptor field, will fire the same signal, and the observer will experience stimuli from only one location (Weinstein, 1968). Low acuity skin only has acuity of one cm, whereas the fingertips can perceive details down to one mm (Weinstein, 1968). As such, body parts with low acuity are subject to tactile illusions (Goldreich, 2007)

Receptor	**Merkel receptor**	**Meissner corpuscle**	**Ruffini cylinder**	**Pacinian corpuscle**
Location	Epidermis	Epidermis	Dermis	Dermis
Response	Slow	Rapid	Slow	Rapid
Frequency	1 - 5 Hz	5 - 50 Hz	15 - 400 Hz	50 - 700 Hz
Perception	Pressure	Flutter	Stretching	Vibration
Receptive Field Size	Small	Small	Large	Large
Responds Best To	Steady pressure from small objects	Rubbing against the skin or skin movement across a surface	Steady pressure & stretching of the skin (e.g., joint movement)	Changing stimuli

Table 1: Summary of the cutaneous mechanoreceptors in the skin low (Wolfe, et al., 2009)

2.1.1 Sensing Vibrotactile Feedback

To best explain the perception of vibrotactile stimuli, two concepts of perceiving texture are relevant to understand (Goldstein, 2007):

Spatial Cues

Spatial cues are tactile cues on a surface, which can be felt when the skin is pressed against the surface, as well as when the skin moves across the surface. Spatial cues help determine shape, size and distribution of surface elements.

Temporal Cues

Temporal cues are tactile cues which can be felt only when the skin moves across the surface, and not when the skin is simple pressed against it. Temporal cues help determine fine texture of a surface in the form of vibrations that occur when moving the skin across the surface.

As aforementioned, mechanoreceptors respond to different properties of tactile stimuli, and the mechanoreceptor to primarily sense vibrations, is the Pacinian corpuscle, as it responds well to high frequencies of vibration, as opposed to slow or constant pressure. And in the case of a virtual object motion, where physical exploratory movement across object surface is not possible, there is a lack of temporal cues, and only spatial cues inform of touch. As such, the brain compensates for the lack of cues, and fills in the gaps, so to speak. Based in prior knowledge and experience, the brain will compensate for lack of receptor signals. It creates the tactile illusion as a consequence of our expectations to the world around us and its behaviour, beyond the constraints of the sensory precision (Knill & Richards, 1996). If such an illusion like the Cutaneous Rabbit can be transferred to a virtual reality application, virtual touching and movement can be an integrated part of the system at a lower hardware cost, but with same effect.

2.2 CUTANEOUS RABBIT ILLUSION

The Cutaneous Rabbit Illusion (CRI) is a simple perception of linear saltation, where there is none. When tapping the skin consecutively and rapidly across clusters of (typically) 3 along the arm, the tapping will start to stray from the points of contact. Instead of experiencing taps at 3 loci, the taps will spread out between the 3 locations, as uniformly spaced taps. The sensation is described as a rabbit, hopping up along the arm.

The number of contact points and taps are not absolute: studies have demonstrated the CRI using various tap frequencies (1 (Miyazaki, et al., 2010); 3 (Asai & Kanayama, 2012) (Bremer, et al., 1977) (Flach & Haggard, 2006); and 4 (Sawada & Zhu, 2014)), and amount of contact points (3 (Asai & Kanayama, 2012) (Bremer, et al., 1977) (Flach & Haggard, 2006), 6 (Sawada & Zhu, 2014), 2 (Miyazaki, et al., 2010)). CRI is often performed on the forearm that holds low spatial acuity, but can also WORK on high spatial acuity skin like the hands and fingertips (Miyazaki, et al., 2010) (Sawada & Zhu, 2014) – and is not limited to the tactile domain. In 1977, Bremer et al. successfully evoked auditory saltation in participants, who were exposed to audio clicking sounds in a horizontal array (Bremer, et al., 1977).

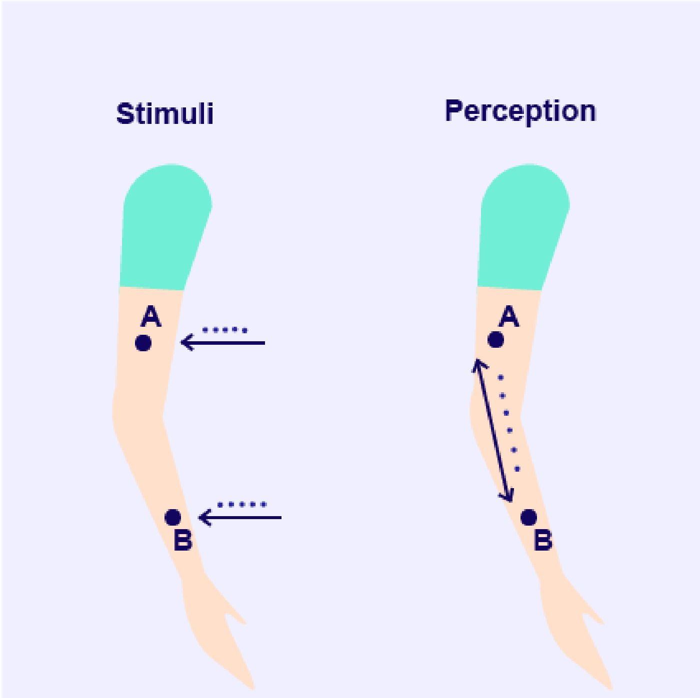

Figure 2: The Cutaneous Rabbit Illusion example; stimuli of 5 consecutive and rapid taps are given at 2 locations (elbow and wrist), but will be perceived at 10 taps distributed evenly in the region between the 2 locations.

The CRI can be categorized in to two fundamental perceptual illusions: the underestimation of inter-stimulus distance (ISD) and overestimation of inter-stimulus time (IST) (Goldreich, 2007). ISD is generally underestimated on skin with low tactile acuity.

The number of contact points, the distances between them, and number of taps are not crucial factors to achieve the saltation effect (note that too many taps, however, can break the illusion) (Bremer, et al., 1977). The most crucial factor is the inter-stimuli intervals (ISI), meaning length of a tap at a contact point– if the ISI is too long, the taps will be perceived at the correct location, and no "hopping" will be experienced. At 200ms the taps will start to stray between contact points, at 100ms the taps will be distributed across between points, and a 50ms the illusion is most vivid (Bremer, et al., 1977). Moreover, the illusion is most effective when IST, meaning the time between taps at a contact point, is same length as the ISI, and when expanding the IST to 3-4 times the ISI, the illusion will break (Bremer, et al., 1977). Increasing inter-stimuli frequency (ISF) (the number of taps per contact point) also decreases the illusion as it helps anchoring the taps. However, no guidelines of maximum ISF has been explicitly given.
In terms of multimodality, tactile stimuli coupled with (temporal and spatial) congruent, visual indication, will produce a more robust illusion, regardless of the tactile direction being upwards or downwards, and spatially incongruent visual feedback will further enhance saltation (Asai & Kanayama, 2012).

2.2.1 Stimuli

In terms of stimuli, only a few studies have investigated the influences of multimodal feedback on CRI (Sawada & Zhu, 2014) (Asai & Kanayama, 2012), where it was demonstrated that the congruency between tactile and visual feedback enhances the illusion, however, visual cues alone are not enough to induce saltation. As tactile stimulus is the dominant modality in tactile illusions (McKenzie, et al., 2012), congruent visual feedback will enhance the illusion, but incongruent (incongruent in the sense that it will not display saltation in the rhythm of the tactile signal) feedback will not modulate CRI, in the sense that it will not decrease the illusion (Asai & Kanayama, 2012).

Thus, the main concern of stimuli is the vibrations, and the properties of the signal. As mentioned, the tactile feedback heavily relies on the ISI, meaning the time between taps at each source point. The ISI must be short enough for contact points not to anchor, while still long enough to be perceived as discrete taps (Bremer, et al., 1977).
Bremer et al. (1977) who used 3 pulses from 3 sound sources (placed in a curve, horizontal line in front of the participant), found that ISI shorter than 50 msec. will distribute the taps evenly between source points.

Sawada and Zhu used Shape-Memory Alloy (SMA) vibrations from micro-actuator wires applied to pinheads of 6mm for vibrotactile stimuli. Stimuli was delivered across 6 pins with an inter-stimulus-distance (ISD) of 3 cm. and a total stimulus time of 1000ms, spread across 4 conditions with ISF varying from 1-4. As such, both ISI (time between pulses per contact point) and inter-stimulus-frequency (number of pulses per contact point) varied for each condition (1 pulse of 200ms, 2 pulses of 100ms, 3 pulses of 66ms, and 4 pulses of 50ms). The tactile stimuli were applied to the palm of the hand, and accompanied with visual matching the supposed saltation. They found that an ISI of 66ms and ISF of 3 created the smoothest movement between contact points.

Asai and Kanayama (2012) used mini motor discs of 10 mm as actuators. 3 actuators were placed on the arm of the subject, at the wrist, the elbow, and midway between the two points, with an ISD of approx. 10-13 cm. Each actuator was accompanied by a LED light that would provide visual feedback, and participants were given a set of headphones playing white noise as background/ambient sounds, to camouflage the sounds from vibrators. The ISF was 3, with a 100ms ISI and an IST of 100ms, meaning that the duration of stimulus sequence for each source point would last 500ms (vibrate 100ms – pause 100ms – vibrate 100ms – pause 100ms – vibrate 100ms).

In the effort to creating CRI on external objects, Miyazaki (2010) used electro tactile stimuli applied to each index finger, with an ISD of 8cm, and a total of 3 pulses – 2 on left index finger, and 1 on the right index finger - with a varying between-stimulus time (BST) that would simulate the illusion of varying jump lengths between the fingers on the external objects (800ms after first pulse, and 50-80ms after second pulse). They found that these values were optimal to generate a “reduced” rabbit – a simple version of the CRI. Headphones were worn to isolate noise generated from the actuators.

It is clear from current findings that a low ISI (>100ms) will create the illusion of tactile saltation. However, the distance between contact points vary a great deal (3cm (Sawada & Zhu, 2014), 8cm (Miyazaki, et al., 2010), 10-13cm (Asai & Kanayama, 2012)), despite ISF remaining low (<4) across all studies. Reasoning behind the choice of distances was not mentioned in either study, and due to the spatial acuity of the contact points (Weinstein, 1968).

2.1 Assessing the Cutaneous Rabbit Illusion

As with most perceptual illusions, the cutaneous rabbit relies on subjective measures to assess whether the illusion was achieved. Previous studies on the CRI have therefore used subjective reports in either verbal or written form.
Bremer et al. (1977) performed a study on auditory CRI, where sound clicks would play from a horizontal array of three sound sources placed in front of the participants, which assessed the effectiveness of the illusion by having participants mark where sounds had occurred and how many times. Prior to each test, participants were informed how many clicks would play in total, and they were asked to mark same name

of sounds on the sheet – had they experienced more than one sounds coming from same location, two marks would be put on the same location on the sheet. Each series of clicks was played twice, before the participants would report their judgements. The results where categorised into three categories:

A) clicks reported at three locations (i.e. no saltation);
B) clicks reported as having spread beyond three locations, but remaining in three distinct groups
C) clicks reported as having spread more evenly (i.e. saltation).

Hoggan et al. (2007) used the CRI to simulate a progress bar to indicate the download status through haptic modality rather than visual, by creating a circular saltation across the index finger, lower thumb and upper thumb. To assess the effectiveness of the tactile display, a within-subject test comparing visual feedback with tactile feedback used temporal reports on when the download was noticed as having been completed. An estimation of the experiences of system interaction was assessed through self-reported ratings on Likert-scales.

The CRI is not confined within our own bodies; Miyazaki et al. (2010) demonstrated that the CRI can also ”hop” onto external objects that are in contact with the subject, like a stick. Participants would touch the ends of a stick with their left and right index fingers. Electrotactile taps would be applied to the tips of the fingers holding on to the stick, and by this, participants experienced the taps hop between the contact points, meaning along the stick. A mechanical slider identical to the stick was used to indicate where participants had felt taps; participants would move the slider’s pointer to the loci where they had perceived taps, and click a button to confirm the marks. Participants were informed of how many taps would occur during each test, prior to it (Miyazaki, et al., 2010).

To simulate tactile stroking on a screen, Sawada and Zhu (2014) utilized the CRI to produce vibrotactile feedback to the backside of the tablet. The vibrations were coupled with visual feedback from the tablet’s screen. Participants would use the left index finger to indicate stroking, while holding the tablet with their right hand to which vibrations were then applied. The illusion was evaluated on the vibrations’ smoothness, comfort, clarity of each vibration, density of perceived vibration, and uniformity of vibration intensity, which was all rated on an interval scale of -3 to +3. Ratings on smoothness and density were used to indicate the strength of the CRI. However, the CRI was not explicitly directed to in the evaluation.

Asai and Noriaki (2014) also demonstrated that multimodality enhances the CRI, if visual and tactile feedback is congruent. A within-subject using a binary reporting system assessed the illusion; participants would indicate tactile saltation with a key press during the test, and would press same key again immediately if no saltation was felt. The response ratios of saltation/no saltation and reaction times from the key presses were recorded and used for evaluation.

The CRI is a subjective experience that does not elicit any immediate physiological response, and thus, evaluation relies on subjective reports on whether the illusion was successful. The most common approach explicitly refers to the illusion via either binary response (you either fail or succeed to experience the saltation), or via marks that describes location and quantity of the taps. Self-reported ratings on the experience in form of Likert-scales like Sawada and Zhu (2014) attempts to assess the experience in more details, however, it is debatable if the items are too implicit, and rather than assessing the actual illusion, it describes experiences associated to the illusion. We feel that an explicit approach will provide a more concrete, tangible insight to how the illusion is affected by the stimuli, and allows for simple comparison between conditions. As for allowing participants to know how many taps they will experience like in the case of (Bremer, et al., 1977) and (Miyazaki, et al., 2010), as opposed to letting participants estimate the amount themselves, this could potentially lead to bias in the responses. In terms of measurement, the relevant and essential information lies in the distribution of taps, and not the number of taps felt, that this study seeks to research.

2.1 Presence

To make a convincing VR simulation, there are several aspects to consider, both in terms of the experience, and in terms of the display. These aspects will be accounted for, and discussed in relations to this project in the following sections, starting with presence, to gain an overview of what it means to feel present in VR.

When put into a virtual environment, it is not uncommon for people to become immersed in their surroundings, and achieving a compelling sense of actually being there in that environment. This is presence; the sense of *being there*. It is an illusion that arises when the perceptual system is manipulated through certain criteria. Presence can be thought of as being comprised of two components that together render a virtual experience as being real; place illusion (PI) and plausibility illusion (PsI) (Slater, 2009)

PI is the sensation of being in a real place, and is reminiscent of presence and Steuer's (1992) telepresence. PI is a direct effect of the perceptual system being manipulated through senses to make you think you are in the mediated environment.

PsI is the perception of events as really happening. It is the cognitive process of experiencing a mediated environment that is congruent to one's expectation of how such an environment should behave and react, causing one's own reaction to be equally natural. PsI occur when virtual events, that you have no direct control over (an external event), refer to you directly. Suppose in an immersive virtual environment, you see a woman walking by and you smile – and she smiles back. An event that you do not directly control (her smiling back) refers directly to you.

In either illusion, the subjects know that, in reality, they are not *there*, and the experiences they have are not real. However, despite knowing this, they still may express same behaviour as they would in real life; if they are frightened, they will scream; if they get excited, they will smile (Slater, 2009).

Creating a compelling virtual environment might then be beneficial in terms of creating the CRI, due to the relationship between PI and PsI. If experiencing PI might sway people to experience PsI, having a convincing virtual environment might compel people to believe what they are experiencing in the virtual world, rather than the real world, thus making the CRI more effective.

2.2 BODY-OWNERSHIP

The Cutaneous Rabbit is a well-known phenomenon and a researched topic. To our knowledge, however, it has never been tested in a VR setting. To simulate same experience in a virtual world, a virtual body to, which vibrations will be applied, is needed. Vibrotactile feedback has so far only been applied to participants' own, physical bodies. To achieve a similar relationship to one's virtual body, it is necessary to establish a sense of ownership over the virtual body.

Body-ownership refers to feeling that the body you are seeing, belongs to you, that it is *yours*. It is an illusion that was introduced back in 1998 by Botvinick and Cohen as "the rubber hand illusion". They demonstrated that through touch and vision, it was possible to facilitate a sense of ownership of a fake, rubber hand (Botvinick & Cohen, 1998). In their study, participants' physical hand was hidden and stroked synchronously as a visible, rubber hand, causing participants to assume ownership of the rubber hand – a sensation was later dubbed body-ownership.

The sense of ownership consists of two main components; the sense of body-ownership and the sense of agency – both of which are based on multimodal, congruent sensory input. Body-ownership refers to the sense of a body belonging to the self (believing that the body you see is in fact yours), while agency refers to the sense of controlling the body part's actions (believing that actions performed are caused by you) (Imaizumi & Asai, 2015) (Tsakiris, 2010) (Tsakiris, et al., 2010) (Tsakiris, et al., 2007).

Agency is related to an awareness, or internal model, of the motor system and its commands (known as efferent signals), and predicts the sensory feedback following said action (known as afferent feedback) (Imaizumi & Asai, 2015) (Tsakiris, et al., 2007). This internal model is the awareness of performing even the simplest action and expecting this will have a certain effect. For agency to occur, this action must be voluntary. If a movement is not initiated by any efferent signals, e.g. if someone lifts your leg, the action is said to be a passive movement.

Passive movement is related to body-ownership alone. The experience of seeing one move will lead to ownership of the movement and the body part that was moved, but not of the action itself. Passive movement will provide afferent feedback (being visual, proprioceptive, auditory, kinaesthetic, etc.), but as there are no efferent signals to generate the movement, it will not be experienced as a result of action by one self. As such, agency relies on voluntary movement. Moreover, agency is affected by the afferent feedback; if it is not congruent with the predicted sensation (e.g. due to temporal delay), the sense of agency will decrease (Imaizumi & Asai, 2015) (Tsakiris, et al., 2007).

Agency and body-ownership can be thought of either being an additive or an independent relationship. The additive relationship model states that agency entails body-ownership, thus agency is a strong cue to body-ownership. The independence model states that agency and body-ownership are two separate, independent experiences, and thus, agency can occur without body-ownership (Tsakiris, et al., 2010)

So, while the pure sense of ownership activates one part of the brain and agency another part, the combination of both ownership and agency will show as a level of body-ownership with the addition of voluntary movement; body-ownership is elicited via multisensory feedback including active movement, and agency will only add to this illusion. The results showed that active movement elicited a significantly higher-level body-ownership, thus supporting the additive model; despite the neural activities involved in the two illusions have no shared activations (Tsakiris, et al., 2010).

These findings are in agreement with other studies that have shown that agency contributes to body-ownership as a combination of afferent and efferent information will create a more coherent sense of ownership (Tsakiris, et al., 2007) (Imaizumi & Asai, 2015).

Slater argues that the body, our body, is a focal point between PI and PsI (described in section 2.1). If you see your virtual body in the place where you perceive yourself to be (i.e. the boundaries of the body schema and body image are accommodated), PI will most likely occur. If you are able to move the virtual limbs and see them moving synchronously in the immersive virtual environment, Psi will most likely occur, as this is an event that relates to you. The relationship between these illusions was also demonstrated by Gonzalez-Franco et. Al. (2010), who found that the stronger the sense of body-ownership is, the greater the possibility for Psi is to occur.

So, to elicit body-ownership, at least head-based motor control, 1PP and a realistic virtual body must be implemented in the system. And these must comply with the body model consisting of body schema and body image. This will automatically birth a sensation of place illusion (due to the virtual body and 1PP) and plausibility illusion (due to head-based motorcontrol) i.e. presence. As such, if presence is part of the body-ownership experience, body-ownership can be measured using the same criteria

2.2.1 Facilitating body-ownership

To induce a sense of body-ownership, congruent multisensory stimuli between the visual, virtual and physical body will facilitate ownership, and that incongruence in sensory stimuli will cause a break in the illusion, as demonstrated by current research.

Using visuotactile stimuli alone, Petkova and Ehrsson (2008) were able to facilitate a sense of full body-ownership of a plastic mannequin. Participants were equipped with an HMD displaying the mannequin from a first-person perspective (1PP). Participants would then experience visuotactile stimuli (being either congruent or incongruent) by being physically strokes on the stomach while seeing and object stroking the mannequin's stomach. Results showed that a compelling sense of body-ownership could be facilitated in the congruent condition, and Petkova and Ehrsson concluded that a 1PP, congruent visuotactile stimuli and a humanoid avatar are critical components in achieving full body-ownership. However, a study by Slater et al. (2010) reported that congruent head-based visuomotor feedback will facilitate a strong sense of body-ownership, regardless of visuotactile being synchronous or asynchronous.

The results of these two experiments are somewhat contradicting, perhaps due to the different experimental setups; Petkova and Ehrsson did not include head-based visuomotor feedback (but instead a fixed position and orientation of a camera) and the avatar was a plastic mannequin rather than a realistic human avatar.

As such, a new set of experiments were conducted by Meselli and Slater (2013) to compensate for the different test setups and to perhaps explain the different results.

Meselli and Slater (2013) found that visuoproprioceptive cues are sufficient to facilitate body-ownership of a realistic human virtual avatar, but a 1PP is crucial. Moreover, body-ownership will be enhanced the higher the realism of the avatar's appearance (the more the avatar looks like a human body).

In general, it is agreed upon that congruent multisensory (e.g. visuotactile) and visuomotor contingencies will enhance ownership further. When using a 1PP and a realistic human avatar, the sense of body-ownership will affect how touch is perceived – asynchronous touch can be perceived as synchronous. Thus, as the level of body-ownership increases, the sensitivity to asynchronous visuotactile stimuli decreases.

2.2.2 Body schema and image

The recognition of one's body and its relative spatial position and orientation, makes up the mental representation of the body; it is how we sit down without looking first, how we avoid collision with objects, how we see ourselves. This mental representation is a fusion between two components; the body schema and body image – and is essential to the self-consciousness (Constantini & Haggard, 2007) (Maravita & Iriki, 2004).

The first component, the body schema, refers to the awareness of the body's physical form and position, and is based on our senses (namely proprioceptive, somatosensory, and visual) that constantly update and inform of the body's physical properties (Maravita & Iriki, 2004) (Constantini & Haggard, 2007). All actions are based on the body schema, as it informs of where body parts are located, and is essential to the spatial coding for actions; it tells us how far to reach for that glass of water, how high to lift the leg to take that step, information on where the body parts are at any time.

The body-ownership is often measured via proprioceptive drift when concerning an arm or hand alone; the perceived position of the physical arm will often be towards the virtual arm, thus showing a change in the body schema, as the internal proprioceptive model has changed (Botvinick & Cohen, 1998).

The other component, the body image, is the cognitive model of the self, also referred to as body semantics. It is combination of the body's appearance and the emotions, that forms the self, and an evaluation of the self (Slater & Sanchez-Vives, 2014) (Constantini & Haggard, 2007). If the body image was to change, e.g. changing racial features or age, the behaviour may change as well (Banakou, et al., 2013) (Konstantina, et al., 2013) (Peck, et al., 2013). When the body is virtually represented, it must somewhat match the body schema and body image.

Tsakiris and Haggard (2005) found that the illusion of body-ownership of a fake, rubber hand would break, when the fake hand was rotated at 90 degrees in respect to the physical hand – showing that the posture of the body or body part must be congruent to the proprioceptive body schema. This also suggests that the sense of body-ownership is not purely a bottom-up process, meaning that it is not merely controlled by sensual inputs.

In the same study, Tsakiris and Haggard also replaced the fake hand with a wooden stick (postural congruent to the physical hand, meaning at a 0 degrees). The proprioceptive drift was even smaller in this condition, supporting the notion that ownership is also a top-down process (as it relies not only on sensory input, but on body schema and body image as well). The third condition included synchronous visuotactile; participants were stroked on their left hand, while seeing a right hand being strokes, which also showed break in the illusion.

Constantini & Haggard (2007) conducted a study on mismatch between tactile and visual stimuli. Participants would either be exposed to; incongruence between seen and felt stroking path; postural incongruence between rubber hand and physical hand, but with congruent stroking path; incongruence of both posture and stroking path. In all three conditions, three levels of incongruence were implemented.

The results show that a postural mismatch has a stronger effect on the level of body-ownership than a tactile mismatch, meaning that the proprioceptive body schema is weighed higher than sensory input in terms of body-ownership – i.e. top-down processes influence the illusion more than bottom-up processes. Constantini & Haggard reported that visuotactile stimuli will only enhance the illusion, when the current proprioceptive state of the body schema is matched.

So, the visual representation of one's body must match both the proprioceptive body schema as well as the body image; impossible postures and unrealistic nonhumanoid features will cause the illusion to break. And visuotactile stimuli will only enhance body-ownership if the virtual representation matches the body schema.

The experience of the body is a combination of top-down and bottom-up processes; the cognitively recognizable objects/images inform of the plausibility of it being part of the body image, and multisensory stimuli manipulate our body schema (Tsakiris, et al., 2007). (Haans, et al., 2008). Body-ownership is an assimilation of multisensory stimuli (bottom-up process) and our internal body references (top-down process). Through multisensory stimuli, the body schema and body image can be recalibrated, leading to a sense of ownership (Tsakiris, 2010).

2.1 Assessing Body-ownership

Body-ownership can indicate to which degree the virtual body appears authentic. To establish validation on later test data, it is important to the project being able to measure to which degree a test participant experienced body-ownership.

As with the CRI, body-ownership is mainly considered a subjective emotion, and is therefore often assessed through questionnaires regarding the experience. Post-testing ratings performed on Likert-scales explicitly asks to the illusion of the virtual body (or body part in question) ("It felt as if the rubber hand were my hand" (Kanaya, et al., 2012); "I felt as if the virtual arm was my arm" (Kilteni, et al., 2012); "During the experiment there were moments in which I felt as if the virtual arm was my own arm" (Slater, et al., 2009); "I felt as if the body I saw in the game might be my body" (Steptoe, et al., 2013); "I felt that the body I saw was my body" (Maselli & Slater, 2013))

Body-ownership can also be assessed through behavioural realism; if one feels ownership over a virtual body, one would display behavioural realism in regards to this body, meaning one would behave in the same manner when events occurred to this body, as one's own body. This assessment has been done by e.g. exposing the virtual body to a threat, to see if this elicits a behaviourally realistic response (Ijsselstein, 2004).

2.2 Discussion

As the initial problem statement reads: "*How will a virtual reality simulation affect the cutaneous rabbit illusion?*" (see section 1.1), the field of interest is to explore how an illusion of saltation might be influenced in a VR setting. Successful demonstration of the cutaneous rabbit illusion in a VR simulation, is relevant regarding the development of tactile displays – especially since such a demonstration might indicate that a high density of vibrotactile feedback actuators is unnecessary. In this train of thoughts, it might be pertinent to consider different directions of the vibrotactile feedback; the cutaneous rabbit illusion has been performed linearly, but, to our knowledge, not curve-linearly. It might be interesting to see if this illusion can also be induced curve-linearly, to explore the boundaries of it.

Current studies differ regarding the values of both the ISF and ISD, though they seem to be somewhat in agreement when it comes to the IST, as most studies have used 50ms (see section BLA). It remains unclear what effect the ISF and ISD might have on the illusion, if any. Although, as mentioned in section BLA, stimuli can start to anchor if the ISF is too high (more than 12). In the interest of creating a compelling illusion, these values will be explored as a preliminary part of the study, to establish which will yield the best results for the main study. The main study will then focus on transferring the CRI to VR, using these parameters that are determined by the preliminary study. As a means of transferring the CRI to VR, the main study will focus on how visual feedback affects this illusion, and how it interacts with the cutaneous sensual system, and possibly how this interaction might break the illusion.

Moreover, as the CRI has been performed outside VR only, i.e. in reality, the feedback given to participants has been given to their bodies directly. To imitate these conditions, the VR setting should include a virtual body, that represents the participants' body in such a way that they will establish body-ownership over the virtual body. It is the expectation that if body-ownership can be established, the CRI should be transferrable to VR. Thus, the main focus of this project will be the visually-dependent effect on linear and curvilinear CRI in VR, with a virtual body.

This has led to the final problem statement:

2.3 Final Problem Statement

How will visual feedback in a virtual reality simulation affect the perception of saltation of linear and curvilinear vibrotactile stimuli?

3. METHOD

The following chapter will account for the method of testing the final problem statement. As the testing will consist of a pre-test, to establish the parameters of the vibrotactile feedback, and a main test, to determine how the visual feedback will affect the CRI, the following sections will account for these tests respectively.

3.1 Testing Method

3.1.1 Materials and Method

As this study aims to research the affordances and constraints vibrotactile feedback in virtual reality, it will test both the variables related to the CRI, and test the illusion coupled with visual feedback, to see how a dominating modality, like the sight, can modulate the perception of tactile stimuli in a virtual environment. In the effort to do so, the study will consist of a pre-test and a main test.

The pre-test will be done outside VR, without visual and auditory feedback. Headphones will, however, be used for passive noise cancelling, to avoid bias because of noise from the haptic display. Previously mentioned studies (section 2.2) have determined that the main factors that influence CRI is the ISI, and have demonstrated that a small ISI is favourable (below 100ms), as long as the pulse length can be perceived as discrete, separate signals. However, the effects of ISF and between-stimuli distance (BSD) have yet to be determined. This first test will seek to understand how BSD affects the CRI, in the effort to reduce the number of actuators needed for a VR suit; if the CRI can be done with a large BSD, the same VR experience can be created at a reduced cost of haptic wear. Moreover, it is necessary to see how ISF also affects the illusion, in the case that a larger BSD can only be achieved with a higher ISF. Up until now, the factor values used in previous research that have not been in focus of the studies, seem somewhat arbitrary, as no reasoning behind the choice in BSD and ISF have been explicitly outlaid. As the purpose of this study is to reduce quantity of actuators through perceptual illusion, it is necessary to see how the illusion compares to actual, tactile saltation. For this, the test will use a strip of mini motor discs, placed in a dense line, which will function as a control test. If the CRI experience matches that of the actual saltation, the experiment will confirm the hypothesis that vibrotactile feedback can be done with a lower number of actuators.

As the CRI has been effectively shown to create a feeling of linear motion, it is also of interest to see if the illusion can be carried out on a curved line. If the CRI can be used to create curvilinear motion as well as linear, it can be applicable to accommodate comprehensive VR tactile feedback needs. In terms of the “feeling” of the illusion, the test will also add a self-reported rating on the compellingness of the illusion (see Table 1).

Q1: How compelling was the feeling of the ball moving up your arm?
Q2: How did you perceive the ball’s movement?
Q3: I felt that the arm that I saw was my own arm (agree/not agree)

Table 1: Questions for the posttest questionnaire.

3.1.2 Pre-test

A total of 17 mini motor discs of 1cm in diameter are placed consecutively in a line, either curvilinear or linear (see Table 2), on a wrap-around sleeve (see elaborated description in design in section 4.3, and implementation in section 5.3).

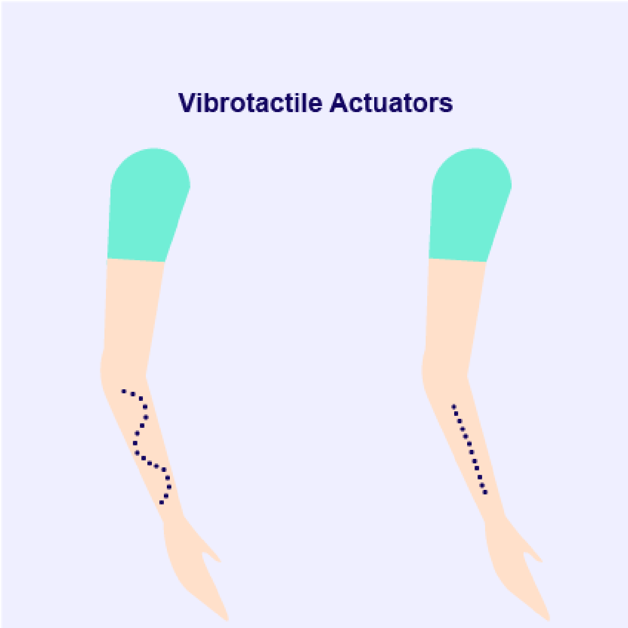

Table 2: Placement of vibrotactile actuators for the between-group tests: Curved (left) and linear (right).

Vibrations from the mini motor discs will be applied to the top of the participant's underarm via the sleeve, and participants will be blindfolded before being equipped with the tactile display, as to not see the placement of the motors or where vibrations are coming from. To avoid bias, participants will also be wearing noise-cancelling headphones, to mask the noise generated by the motors. The vibrating sequence will loop at the participants' request, until they are ready to evaluate. Once ready, a questionnaire will be given, before continuing to the next condition. The total elapsed time of each vibration sequence will vary according to condition (see section Table 3, Table 4, and Table 5).

The first experiment will consist of a between-groups test on either curvilinear or linear motion, where each will test BSD and ISF within-group with an ISI of 50ms. The within-group test will be a 2 by 3 design; three conditions on BSD of 0 (control condition), 3, and 7 cm, and a total ISF of either 9 (see Table 3), 15 (see Table 4) or 30 (see Table 5)(distributed evenly across the contact points), constituting the following variations:

- 17 taps distributed on 17 vibrators (control) (Table 4)
- 9 taps distributed on 3 vibrators (V3T9) (Table 3)
- 9 taps distributed on 5 vibrators (V5T9) (Table 3)
- 15 taps distributed on 3 vibrators (V3T15) (Table 4)
- 15 taps distributed on 5 vibrators (V5T15) (Table 4)
- 30 taps distributed on 3 vibrators (V3T30) (Table 5)
- 30 taps distributed on 5 vibrators (V5T30) (Table 5)

After the test, participants will fill out a questionnaire on distribution of taps and the compellingness of the illusion being in a continuous motion, and the compellingness of the illusion being a saltation motion on a 7-point Likert scale (see Table 1). To assess the distribution of the taps, the questionnaire will include an outline of an underarm, where participants will mark where and how many times they felt taps. This will assess both how many taps were perceived, in what directional movement, and how the motion was distributed across the arm (being either dense or evenly distributed).

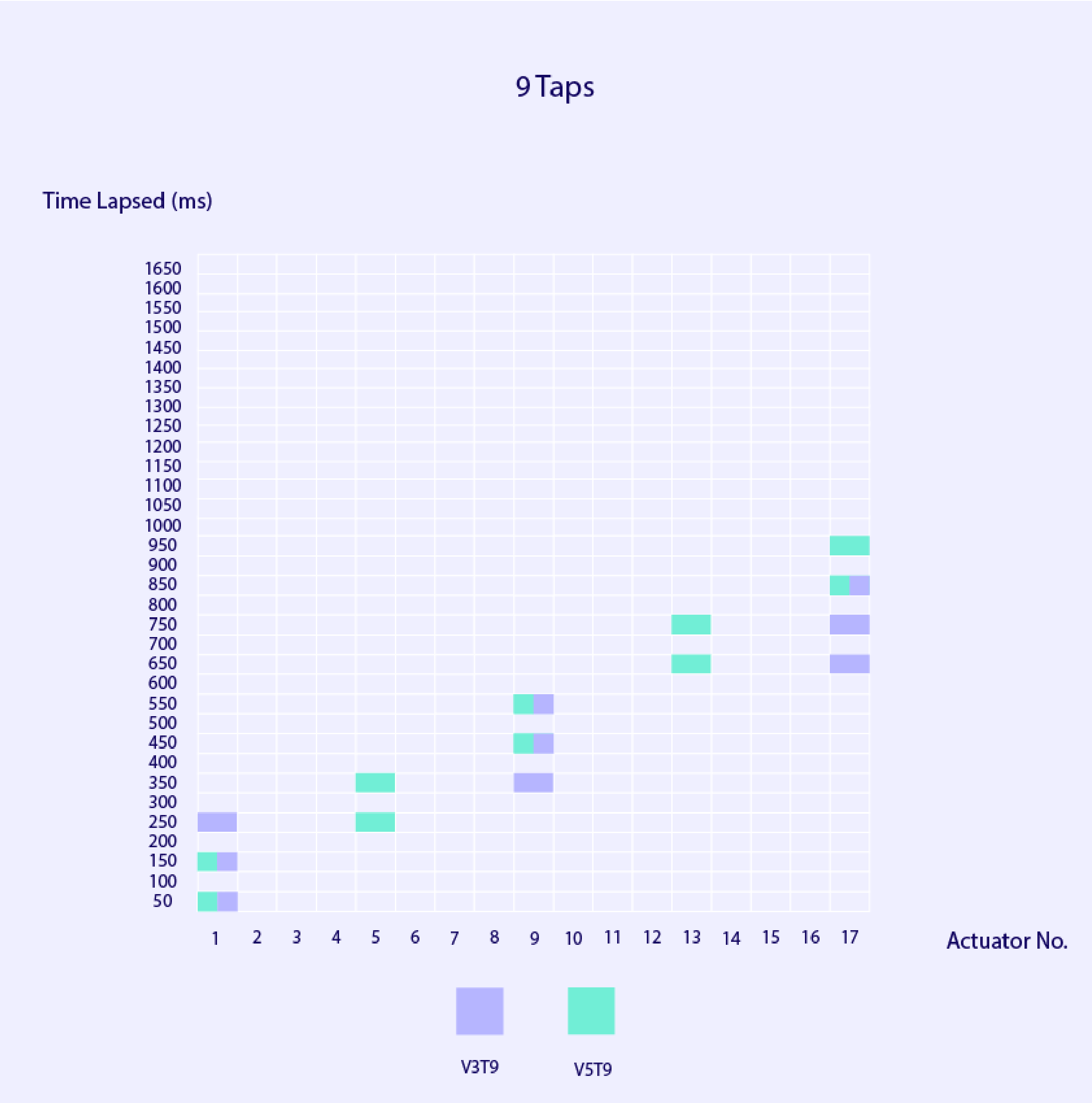

Table 3: Time elapsed while applying stimuli across motors for the V3T9 condition, where every 8th motor fires 3 times, and the V5T9, where every 4th motor fires 2 times.

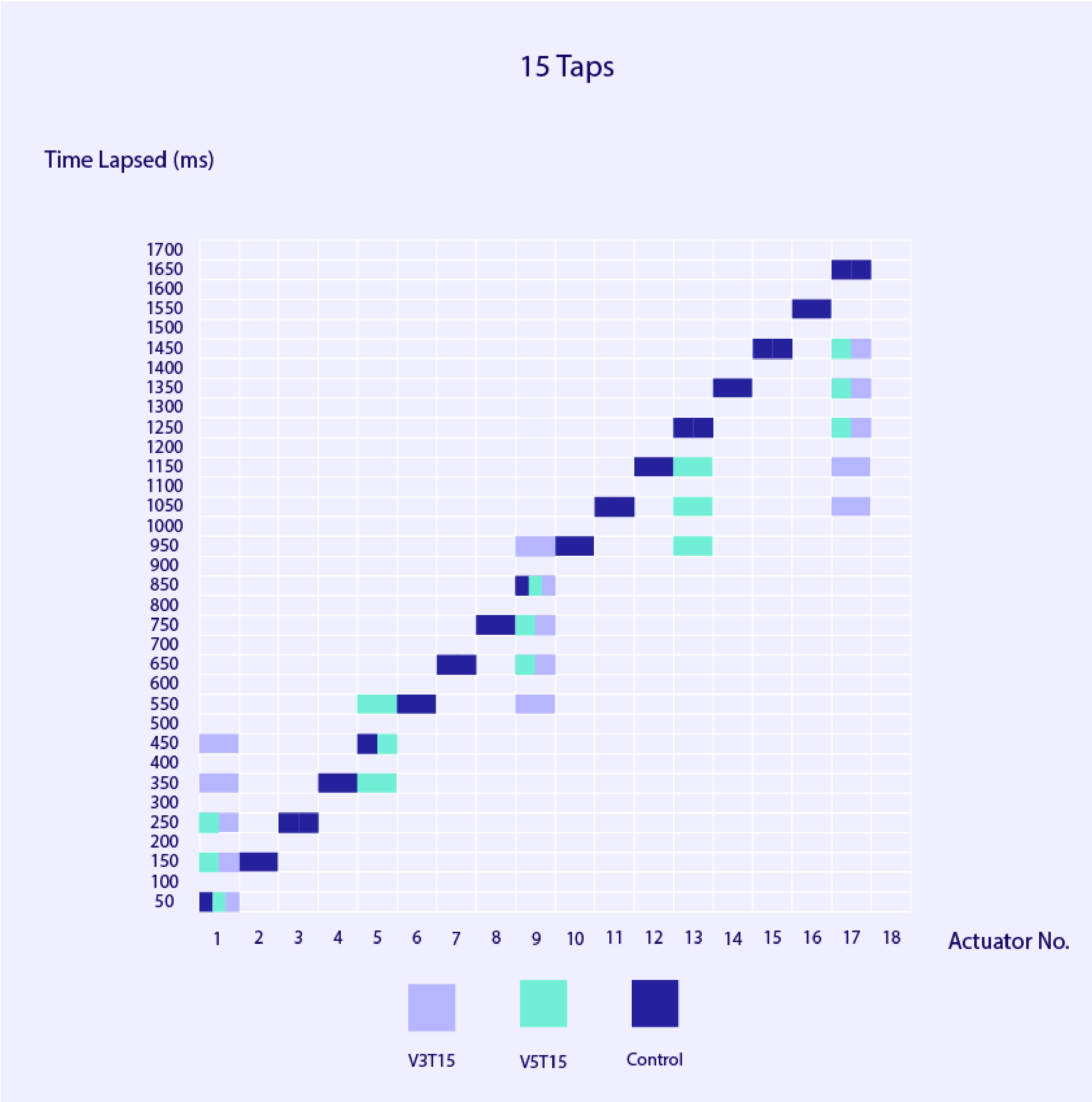

Table 4: Time elapsed while applying stimuli across motors for the control condition, where every motors fire once, the V3T15 condition, where every 8th motor fires 5 times, and the V5T15, where every 4th motor fires three times.

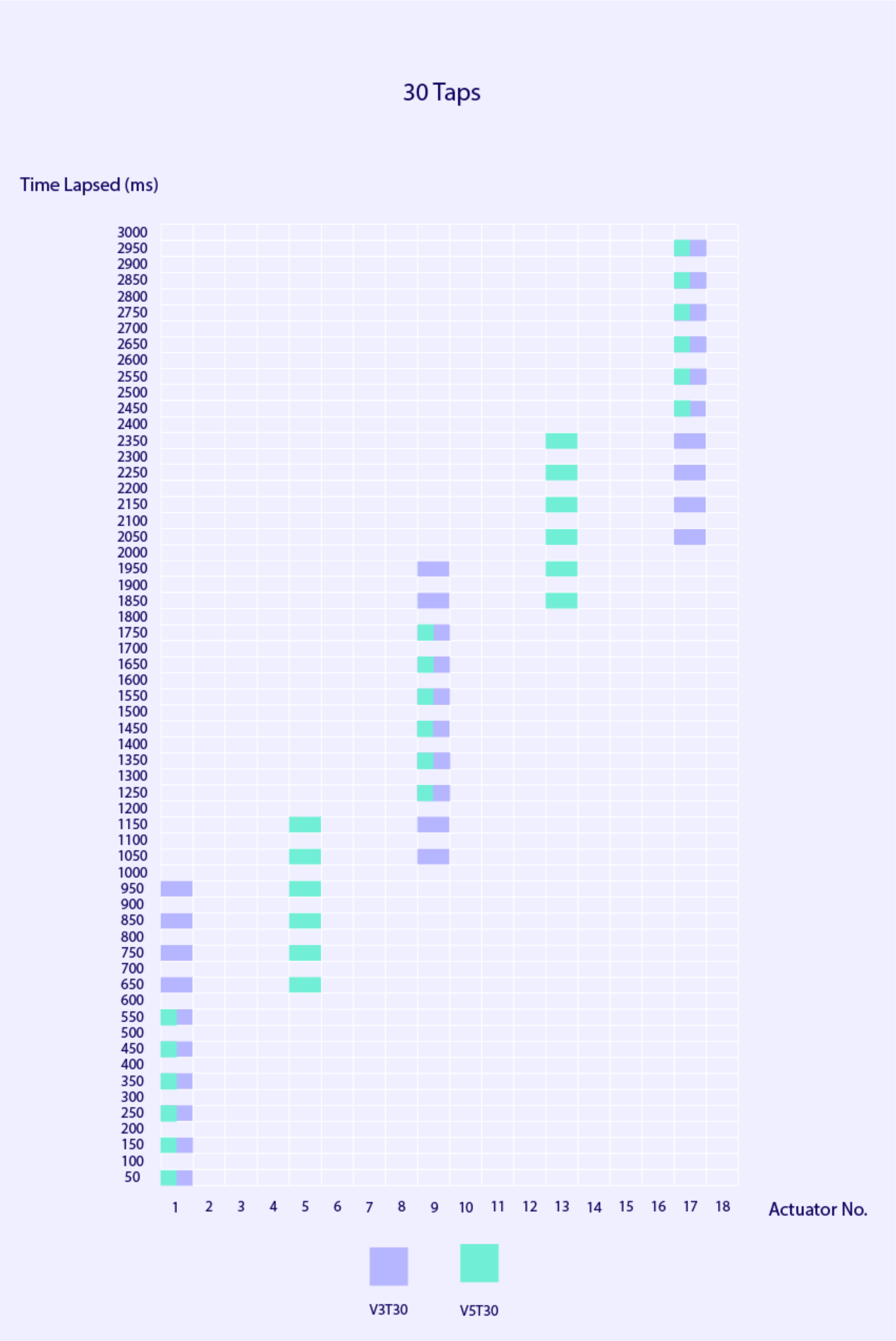

Table 5: Time elapsed while applying stimuli across motors for the V3T30 condition, where every 8th motor fires 10 times, and the V5T30, where every 4th motor fires 6 times.

3.1.3 Main test

The main experiment will test the CRI in a virtual environment, consisting of visual feedback. Participants will sit in front of a table, where they will experience the virtual environment through the Oculus Rift head-mounted display (HMD). After having put on the HMD, a sleeve will be put on the participants' arm, by the conductor, to which the motors are mounted. As with the pre-test, this is done blindfolded (by the HMD) to avoid any bias on direction and placement of the vibrations.

The virtual environment will be a simple room (see description in section 4.2 and 5.2), where participants will sit in front of a table mapped to the physical table in front of them. The table should induce a sense of body-ownership due to the visuotactile feedback along with the visuomotor feedback from the Oculus Rift – they will see their virtual body move as their own, and experience the same feedback as they would in the real world. The virtual arms and hands will move according to the physical movement, while the rest of the virtual body remains in a fixed position. A computer screen will sit on the virtual table, on which the post-test questionnaire will be displayed after each condition.

Stimuli

Based on results from the pre-test (section 3.1.2), the vibrotactile feedback accompanying the ball movement will use same values as V5T15 and V3T15.

Four types of visual feedback listed below, will be coupled with the values of abovementioned conditions:

1) Linear, hopping ball movement
2) Linear, smooth ball movement
3) Curvilinear, hopping ball movement
4) Curvilinear, smooth ball movement

Once the participant is set up, the test sequence will commence, constituting a total of eight conditions within each test of either curved vibrotactile feedback, or curvilinear vibrotactile feedback. A virtual ball will move from its place on the table, to the participant's virtual wrist, from where it will move across the virtual underarm, accompanied by vibrations from the motors.

The virtual arms will be free to move as the participants, controlled by the Oculus Rift hand controllers; they will hold one controller in each hand, which enables tracking of arm movement, and to engage with the questionnaire on the virtual computer screen.

As in the pre-test, assessment of the stimuli distribution will be done through an outline of an arm with a grid-overlay, where participants will mark where and how many times they felt taps. The thumb stick of the Oculus controller will be used to navigate through the grid (see Figure 3), and the right trigger will mark the number of perceived taps, and the left trigger will remove a mark (see Figure 4).

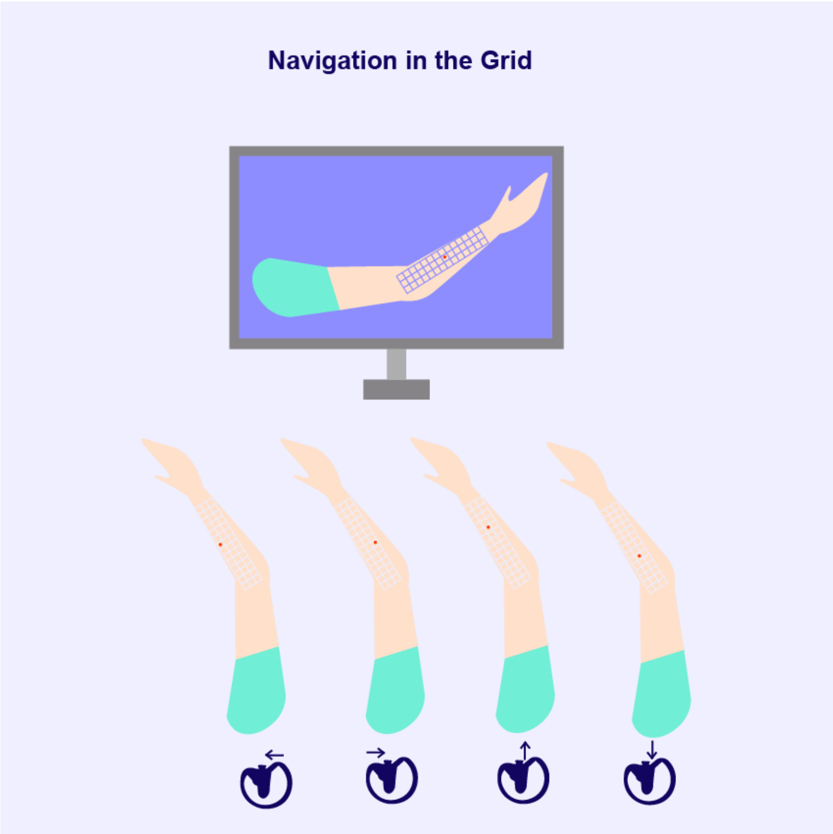

Figure 3: Thumb stick navigation in the arm grid from the questionnaire.

Figure 4: The B and A buttons of the right controller are used for marking and unmarking in the questionnaire.

The compellingness of the illusion and level of body-ownership will be rated on a 7-point Likert scale, and participants will be asked to rate compellingness on both continuous and hopping motion, to assess how the motion was experienced. It is expected that if one of these ratings is rated as very compelling, the other will not be compelling at all. These ratings will be done via a slider on the screen, which participants can swipe left and right with the B and A buttons of the right controller. To go back and forth between items on the questionnaire, the right- and left-hand trigger will be used. Once the questionnaire has been filled out, the next condition will commence, and thus, participants will not leave the virtual environment until after having experienced all conditions.

4. DESIGN

The following chapter will account for the design of this project, both in terms of the experimental design, and thus an extension of the methodology chapter, and the design of the prototype. This chapter will consist of design choices in regard to the physical setup, the virtual environment (hereunder the visual design of the post-test questionnaire, as described in section 3.1.1), and the prototype sleeve, hereunder the design of the iteration process that followed pre-testing.

4.1 Physical Setup

The physical setup of the experiment (see Image 1) will have the participant seated in a chair, as the sole focus will be on the participant's arms, rendering full body movement irrelevant. There will be a table in front of the participant, on which they can place their arms. They will be given a set of controllers, to use when navigating around the post-test questionnaire (see section 3.1.1). Participants will wear the prototype sleeve (see section 4.3 for further description) on the forearm, with the vibrators on the top of the arm, on the hairy skin, and a breadboard circuit mounted over the sleeve, as seen on Image 1). On the upper arm, they will be wearing another sleeve, which holds the microcontroller. Additionally, participants will wear a head-mounted display which enables head movement in the virtual environment, and a set of headphones for passive noise cancelling.

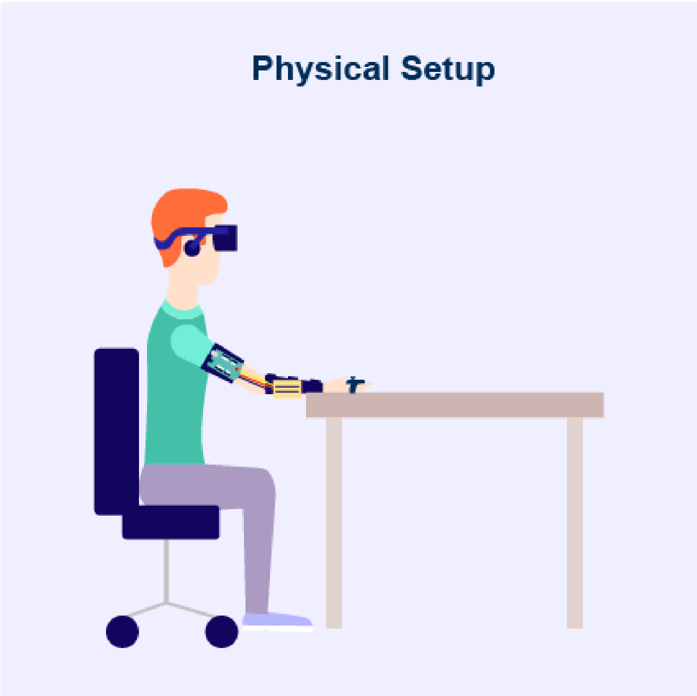

Image 1 the physical setup of the experiment.

4.2 Virtual Environment

The virtual environment will be somewhat corresponding to the physical setup (see Image 1) (see section 4.1); there will be a virtual humanoid avatar, corresponding to the position and orientation of the participant (see Image 2). The movement of said avatar will be limited to head movement and movement of both arms. The prototype sleeve will not be visible in the virtual environment, however, on the table will be a screen, for the purpose of displaying the post-test questionnaire (see post-test questionnaire in section 3.1.1). The controllers that the participant will be physically holding, will be virtually represented as well, to make using them easier and more intuitive, as they will be used for navigation inside the virtual environment.

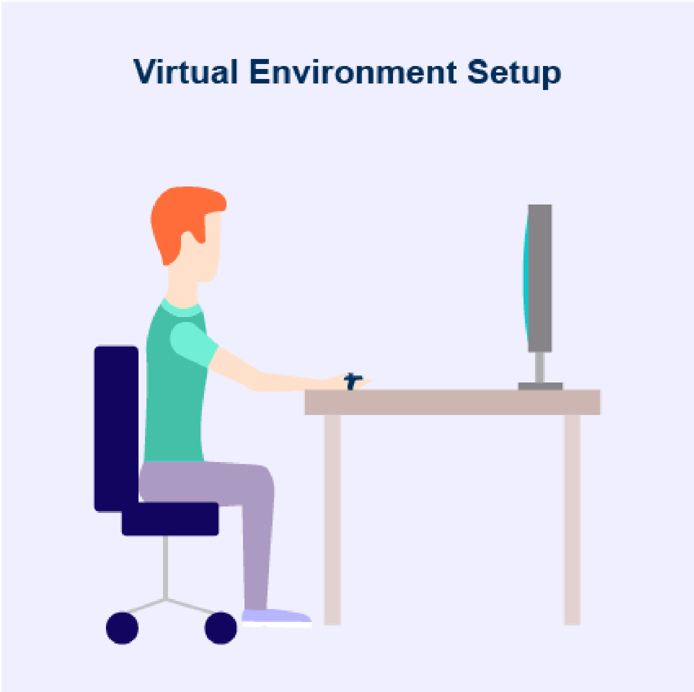

Image 2 the setup of the virtual environment.

4.2.1 Post-test Questionnaire

As described in section 3.1.1, there will be a post-test questionnaire for self-reported ratings in regard to body-ownership, and how the participant perceived the tactile events of the test. As mentioned in section 4.2, there will be a screen in the virtual environment for the post-test questionnaire. Having participants fill out the questionnaire, while still in the virtual environment, will be time efficient as opposed to taking all the equipment off between each test, seeing as it is a within subject design, and each participant will have to go through the procedure of tactile event, followed by a post-test questionnaire, seven times. Furthermore, it will not cause breaks in the illusion of presence, as the entirety of the test will take place in the virtual environment, thus not reminding the participant that it is not the physical world they are experiencing.

The post-test questionnaire will be displayed on the virtual screen and consist of questions regarding body-ownership, and a grid to mark the position of the perceived taps. The questions, which will be ratings on a 7-point Likert scale (see section 3.1), will be displayed on a 0-6 scale, rather than a 1-7, to make it more intuitive. The lower extreme of the scale, will be labelled “Not at all”, so in that sense, coupling that with 0 might make more sense.

The reporting on the perceived tactile event will be an image of the virtual humanoid arm, with an overlay grid of boxes corresponding to the number of possible positions of the mini motor discs on the arm.

Participants should be able to shuffle between the boxes, and put in numbers to mark where and how many times they felt taps. The grid should have a neutral colour, which is easily distinguishable from the colour on the particular box the participant is currently hovering over to mark the perceived tap.

4.3 Prototype Sleeve

The following section will account for the design choices of the prototype sleeve, which will be the tactile display for this project.

The vibrators, which will apply the tactile feedback, should be held in place on the arm of the participant, which is why a sleeve of sorts will be made for this purpose. The sleeve should be adjustable in girth, to accommodate a variety of different sized arms. As for the length of the sleeve, adjusting this would be impractical, as this would require adjusting the vibrators for each participant, or finding participants all with the same size arm. Therefore, the length of the sleeve should not exceed 24 cm; this should fit the majority of people.

The vibrators should be under the sleeve, so that they are in direct contact with the skin, to avoid the vibrations getting absorbed by the materials of the sleeve. Moreover, participants should not be able to see the placement of the vibrators, as this might cause bias in the test. The vibrators should be placed so they are not in physical contact with each other, to reduce the noise they make when they vibrate, so the participant is not made (auditorily) conscious of the vibrations. The dimensions of the vibrators should be as flat as possible, so they are not clearly visible under the sleeve, and with a diameter of approximately 1cm, as this would cover the size of a Pacinian corpuscle mechanoreceptor's receptive field (see section 2.1.1).

As the method chapter states (see section 3.1), there should be a linear- and a curve-linear path of vibrators. Thus, the vibrators should be mobile, in the sense that it should be possible to move them around for respectively the linear- and curve-linear path. To enable this mobility, the vibrators should be fixed on Velcro, so they are easily moved, yet secure once placed.

To avoid having to slide the sleeve over the hands, and risking moving the vibrators while doing so, the sleeve should be openable along the side, so the sleeve will be wrapped around the arm, rather than slid on. This is also to be done using Velcro, as adjusting will be time efficient, and it will accommodate all girths (see Image 3).

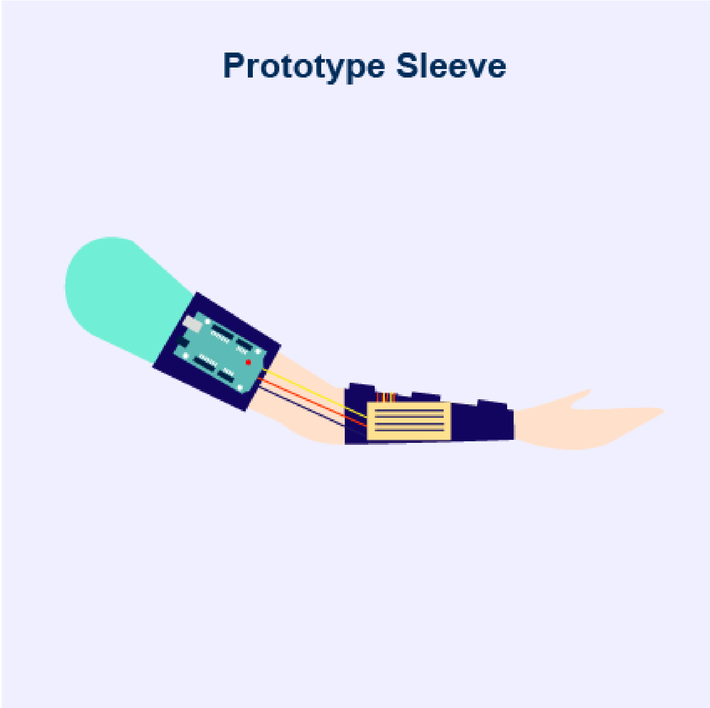

Image 3: The prototype sleeve, connected to a sleeve holding the microcontroller.

The arm with the sleeve on should have as much mobility as possible, as to not remind the participants that they are wearing it, to make the virtual environment more believable. The vibrators will be connected to a breadboard circuit, which in turn is connected to a microcontroller (technical elaboration on this will be done in the implementation chapter 5.4). The breadboard circuit and the microcontroller should be mounted on the arm as well, to sustain mobility. These will be mounted on respectively the sleeve for the underarm, and another sleeve for the upper arm (see Image 3).

4.3.1 Iteration Process

Pilot test

A pilot test of the experimental design was performed, to reveal any weaknesses in regards to understandability of the questions, understandability of the conductorial introduction to the test, and usability of the physical interface, i.e. all navigation with the controllers during the entirety of the test.

The pilot test showed a problem with the post-test questionnaire, where participants were asked to mark the perceived taps on a grid (see section 3.1). The arm displayed on the screen, was placed horizontally, while the participants actual arm (as well as the humanoid avatar in the virtual environment) was placed on the table in front of them in a zero-degree angle. With this position of the arm, it was hard for participants to “translate” where they had perceived the taps. The position of the arm on the screen should be changed, to better match the position of the participant’s arm. Thus, it will we rotated 90 degrees, so it is vertical on the screen (see Image 4), for more intuitive self-reported rating.

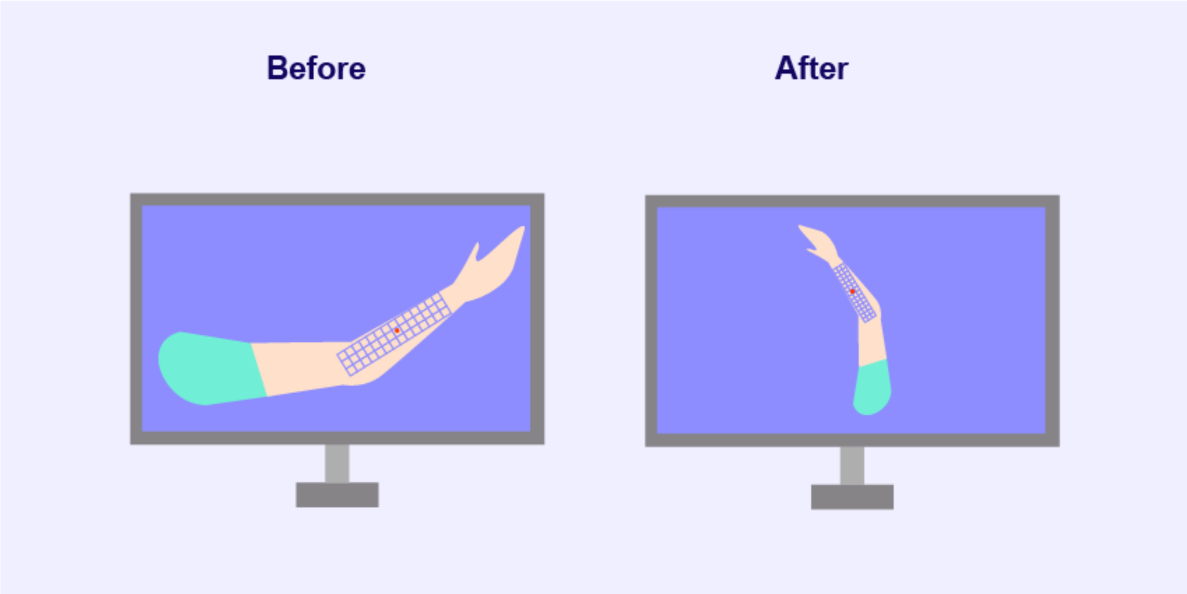

Image 4 before and after image of the design of the screen with grid for marking perceived taps.

Furthermore, the participant reported some confusion regarding the use of the controllers, though they had been introduced to the usage of the controllers before the test, and though it was explicitly written before each scene how to use the relevant controls. To avoid this confusion, the buttons on the virtual controllers should be changed, so they have colours, and any reference to the buttons (either oral by the conductor or written in the virtual environment), should refer to the colour of the button, instead of the name; i.e. the A button on the right-hand controller should be referred to as the orange button.

Pre-test

Pretesting showed that having the entire circuit mounted on the arm was impractical, and decreased mobility: The wires were a nuisance when bending the arm, and furthermore, the wires got crossed (both under the sleeve and over), making the circuit unstable. Thus, the design of the prototype sleeve was iterated, to correct these limitations and faults.

To solve problematic of the immobility of having the whole circuit mounted on the arm, both breadboard circuits and microcontroller should be in separate boxes, to keep the wires from crossing, and to keep the entire circuit manageable (see Image 5). To make the wires from the vibrators manageable, they should be sewn onto the sleeve (see Image 6), so they do not cluster and make the sleeve fit unevenly on the arm.

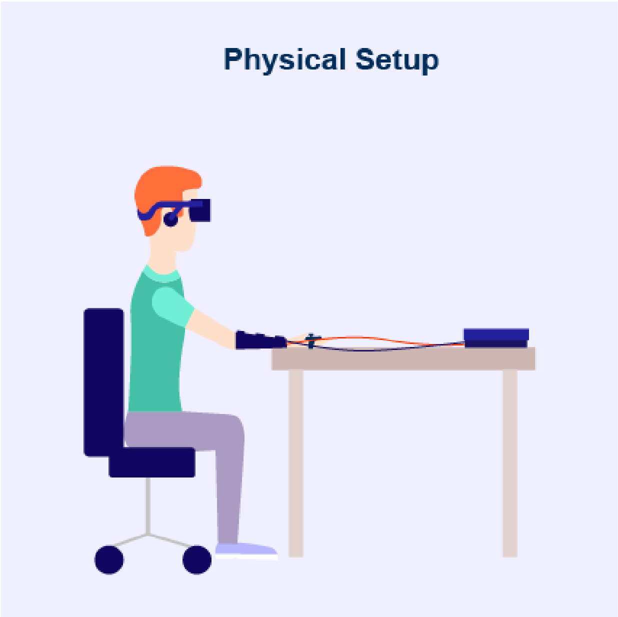

Image 5: The physical setup: participant wearing the prototype sleeve and a head-mounted display, while holding a controller.

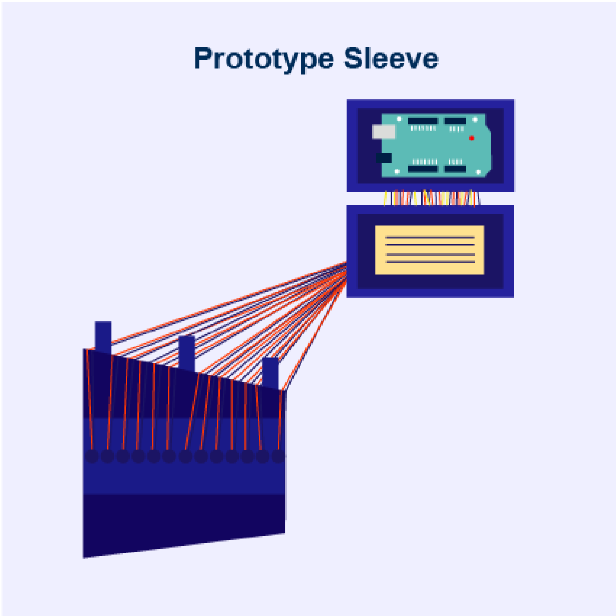

Image 6: The prototype sleeve, connected to the breadboard circuit, which connects to the microcontroller.

5. IMPLEMENTATION

The following chapter will account for the implementation process of this project. This chapter will preliminarily cover the physical setup, hereunder an introduction to the audio, visual, and tactile display, to provide a general overview. The final virtual scene will be accounted for in terms of aesthetics. The tactile display will be accounted for, both in terms of physical design and vibrotactile feedback, as well as the interaction with Unity, which will lead to the setup with the virtual body. Finally, the implementation of the post-test questionnaire will be elaborated upon, with focus on the functionalities of navigating around between questions, and mark ratings.

5.1 Physical Setup

The following section will account for the final physical setup, as it was during the test.

The physical setup of the test had participants seated in a chair, which was placed in front of a table. On the table, there was a computer screen, connected to a stationary computer under the table, which contained the Unity project (see section 5.2 for elaboration on the virtual setup). Furthermore, the boxes containing the breadboard and Arduino (as described in section 4.3.1 and section 5.3), were also placed on the table, in the far-left corner, to avoid participants touching them.

Image 7: The physical setup, while a participant is testing the experience.

5.1.1 Auditory and Visual Display

Participants would be wearing the Oculus Rift CV1, and holding the associated controllers (see section 5.5 for elaboration on functionality) (see Image 7). There was no implemented auditory feedback in the virtual scene, but participants would be wearing Audio Technica M-50X headphones, for passive noise cancelling.

5.1.2 Tactile Display

Participants would be wearing a tactile display on their left forearm, which connected to the breadboard and Arduino on the table, via a collection of 70cm long wires from the mini motor discs (see section 5.3).

5.2 Virtual Setup

The following will provide a brief overview of the virtual setup in terms of the visual design.

The virtual setup of the test will be very simplistic, as to not take participants' focus from the objective, which is watching the virtual ball, as it moves up along the virtual arm. The immediate surroundings of the virtual environment (VE), will be somewhat corresponding to the physical setup; there will be a virtual body, which will be seated in front of a table. On the table, will be a computer screen, however, on the virtual computer screen, the post-test questionnaire will be displayed.

There will be placed two floor lamps and one loft lamp as light sources in the VE, which will be the only other objects in the room. The walls will be white, and the floor will look like grey vinyl, corresponding to the walls and floor in the lab where the test is conducted.

5.3 Prototype Sleeve/Tactile Display

The implementation of the tactile display will be accounted for in the subsequent section, in terms aesthetics and functionality. Hardware specifications, and elaboration on the circuit in general, can be found in section 5.4.

The tactile display is a prototype of a sleeve, which provides vibrotactile feedback (see Image 8). The sleeve itself is made of cotton. Rather than stitching the sleeve shut, it will be wrapped around the arm, and shut by Velcro (as described in section 4.3). The sleeve is 20cm long, and has a width of 15cm at the wrist, and 25cm at the elbow. There are three horizontal strips of Velcro of 15cm by the wrist and 20cm on the middle and near the elbow, to shut it with for easy adaptation to varying arm girths.

On the inside of the sleeve, 2x5cm wide strips of Velcro were sewed onto the entire length of the sleeve. The purpose of the Velcro, is easy modification of the shape of the mini motor discs that will be mounted onto it. On the Velcro, the shape of the intended curved path for the mini motor discs was outlined using a red marker, to ensure all participants would experience the same curve of the path, should the need to move the mini motor discs occur. A piece of 1x1cm Velcro was glued onto the bottom of each mini motor disc, so they could be secured on the Velcro in the sleeve.

Image 8: The tactile display, and the associated boxes containing respectively the breadboards and the Arduino, as seen with and without lids.

70cm of extra wire was soldered onto each mini motor disc. They would be placed densely in the sleeve, so to avoid the bare tin to form connections, each soldering point was encased in glue, to stop it from conducting. Furthermore, to avoid the wires from clustering, each wire was separately stitched onto the sleeve, to keep them in an ordered line. Each mini motor disc was numbered corresponding to the number on the associated circuit in the breadboard. This was done to easily being able to find the fault, should any of the mini motor discs fail to fire.

The wire from the mini motor discs were connected to five breadboards (see section 5.4.1). The breadboards were placed in a bow in a row, separated by cardboard walls, to avoid unwanted connections between breadboards. From each breadboard, the wires to be connected to the Arduino (see section 5.4.1) were put through holes in the box, and through holes in a different box containing the Arduino. In the box containing the Arduino, two conducting rows of female crimping pins were placed, to connect the wires. The rows were then, in turn, connected to the Arduino.

5.4 Vibrotactile Feedback

This section will explain the technical specifications of the vibrotactile feedback. This will be done in terms of hardware, i.e. the mini motor discs, and the circuit they are part of, and the connection between the Arduino and Unity.

5.4.1 Hardware

Haptic feedback can be generated from various motors; Linear resonant actuators, eccentric rotating mass, audio transducers, etc. For this project, coin vibration motors were used. The motors resemble a coin in its size and shape, hence its name, and are generally very small in size – the motors used in this project were of Ø10mm – and due to the requirement of the taps being close together and for the purpose of performing a control condition, a "true" saltation, over a small area (the forearm), the motors needed to be small of size.

The coin motors are eccentric rotation mass (ERM) vibrators, work by the principle of moving mass to create unbalanced of the object it is attached too. The ERM rotates the unbalanced mass around its axis, controlled by a direct current (DC) signal, causing spatial displacement, which is what we perceive as vibrations.

The DC signal controls when the motors are active, and as opposed to alternating current (AC) motors, the coin motors work in a binary fashion and can only be either on or off, which would be adequate for the purpose of this project. The pre-test needed a control condition simulating a true saltation for comparison purposes, and as such, a compact array of vibrators that would each would fire once was needed. The size and simple mechanism of the coin motors were fitting for this.

A total of 17 coin motors, placed consecutively in an array. The motors were connected in a parallel circuit, allowing for separate control for each motor, which was needed for the ISF and BSD variables in testing. The voltage sent to the coin motors were controlled by the Arduino Mega 2560 microcontroller. With the Arduino, the DC output can be controlled through programming, allowing for more dynamic control. The Arduino simple sends a signal of either 1 or 0 to a pin, telling the pin to send voltage through or not. The sensor, or in the case motor, connected to the pin will receive the DC signal

In Figure 5 and Figure 6 the schematics and breadboard illustration of the circuit can be seen. The circuit included diodes, capacitors, and transistors for voltage and current regulation. Motors have been known to create voltage spikes as the mass rotates, which may create voltage spikes that can potentially damage the Arduino. To avoid this, diodes were placed in the circuit to function as a valve between the Arduino and motors. The capacitors sore the possible voltage spikes and keeps the electric current smooth. Moreover, current from the Arduino is somewhat weak, so transistors were used to amplify the current. However, to avoid too much current flowing to the motors, which could damage them, a resistor was put in between to divide the voltage.

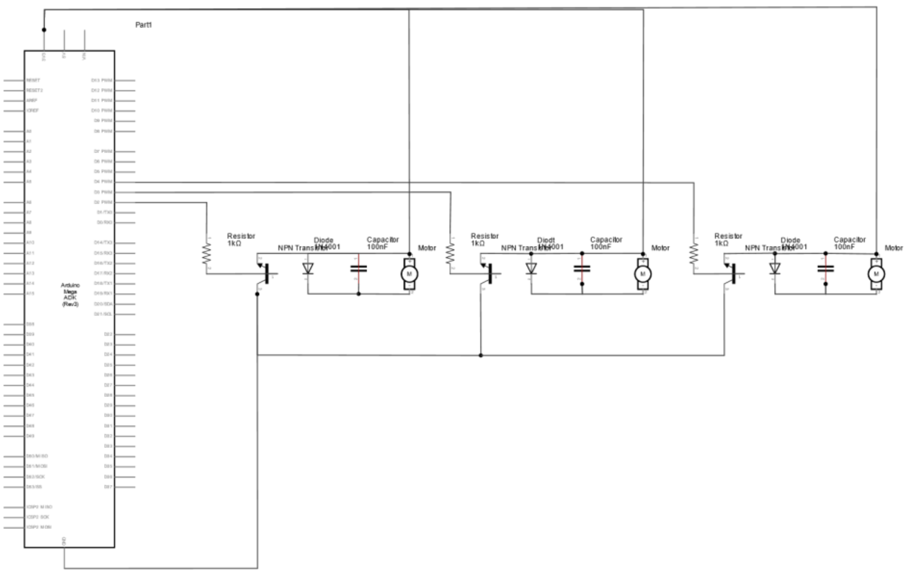

Figure 5: Schematics of the circuit used to control coin motors (only 3 motors included in this example)

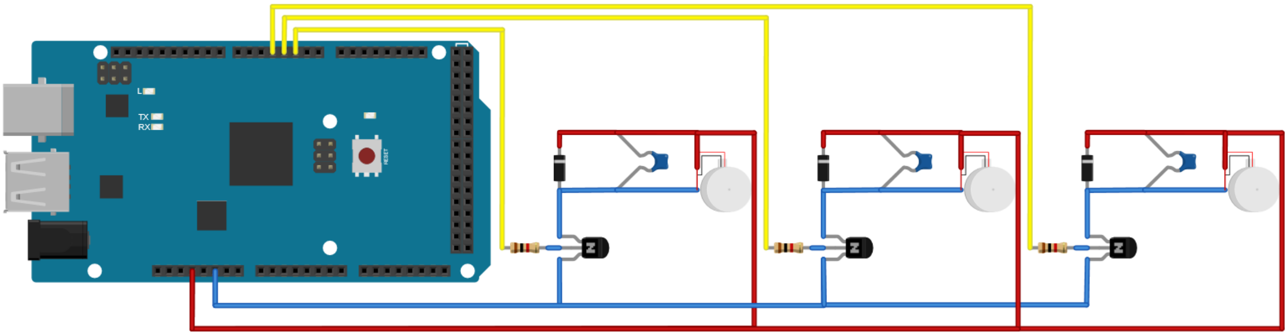

Figure 6: The Arduino and the parallel circuit of coin motors (only 3 are included in this circuit)

5.4.2 Unity and Arduino

Arduino was integrated with the Unity application through a serial connected. The serial communication would connect to a specified port, to which the Arduino was connected via USB, and data was sent from Unity to Arduino over the serial line. Unity would send a send a message through the connection containing a number representing a pin, and Arduino would send a digital signal to this pin to fire.

In Unity, the serial message was sent in a separate thread to the port, rather than in Unity's own update function. Sending and receiving message between Unity and Arduino can cause bad framerate, as these methods are blocking calls, and will not return before completed, which will cause Unity Update (which is called every frame) to hang until then, causing a bottleneck of data problem.

To avoid this lag, the serial connection was set up using threading. Threading is essentially having another separate thread run outside Unity's main thread. This means that if the serial write and read calls are blocking the thread, the Unity main thread remains unaffected as will the framerate.

Unity will send a message containing the number of the pin Arduino will activate (see Code snippet 1) through the Write() method, which essentially writes a message to the serial monitor which Arduino then reads.

```
if (stream.IsOpen)
            {
                try
                {
                    if (on == true)
                    {
                        SendMsg = pinNo.ToString()+ "\n";
                    }

                    else
                    {
                        SendMsg = "21\n";
                    }

                    stream.Write(SendMsg);
                }

                catch (System.Exception e)
                {
                    Debug.Log("Serial stream is not open: " + e.Message);
                }
            }
```

Code snippet 1: Unity sending string to Arduino via the serial stream

Arduino will read the serial monitor, however, as the message is sent in bytes and the number from Unity may consist of two digits, it is necessary to convert the separate bytes into a complete string. To be able to differentiate between messages, Unity will send the pin number followed by the delimiter “\n”.

As seen in Code snippet 2, Arduino reads the message, and stores the bytes in an integer, and will continue to add each number until reading the delimiter value. If Unity for example tells Arduino to play pin number 15, Arduino will receive the bytes 1 and 5 separately, which then needs to be reassembled in the code.

```
if (Serial.available() > 0)
    {
        integerValue = 0; //reset current pin number
        while (1)
        {
            incomingByte = Serial.read();
            if (incomingByte == '\n') break; //exit when receiving delimiter
            if (incomingByte == -1) continue;
            integerValue *= 10;

             //converts ASCII to integer
            integerValue = ((incomingByte - 48) + integerValue);
        }

        if (integerValue >= 0 && integerValue < 20)
            digitalWrite(pins[integerValue], HIGH); //turn on current pin
        else
            turnOff = true; //turn off all pins
    }
```

Code snippet 2: Arduino reading the message from Unity by storing bytes into string and converting these to int

The pin number sent from Unity is controlled by the virtual ball's current placement. The ball's movement is determined by several waypoints placed in the virtual scene, which will dynamically be put in an array. The ball will continue to next waypoint over 50ms, and then pause for 50ms before continuing to the next waypoint (the form of the waypoints determine whether the ball moves in a linear or curvilinear path). Whenever the ball is moving towards next waypoint, Unity will stop sending the current pins number, thus Arduino will turn off all pins. When the ball is pausing, Unity will send the pins number again.

5.5 Virtual Body

Participants entered the virtual environment through the Oculus Rift CV1 head-mounted display (HMD) (Figure 7) and the Oculus Touch controllers (seen in Figure 9). The Oculus HMD has a field of view of 110 degrees and a resolution of 2016 x 1200, and allows for 360° view of the virtual world. On its own, the HMD is able to track orientation through its integrated gyroscope, magnetometer and accelerometer, however, when combined with the Oculus sensor (Figure 8), positional tracking is possible of both the HMD and hand controllers. The sensors are infrared cameras that track the movement of the devices that themselves had micro infrared LEDs embedded (Oculus, u.d.). Same principles for HMD are used for the hand controllers, allowing for orientation and positional tracking of the controllers as well.

Figure 7: The Oculus Rift CV1 HMD

Figure 8: The Oculus Sensor for positional tracking

Figure 9: The Oculus Touch hand controllers

To induce a sense of body-ownership (as established in section 2.2), a virtual body was included in the scene, and participants were to be able to move the virtual arms, to establish body-ownership. Participants would hold hand controllers in their hands, and the tracked position and orientation of these, was mapped to the virtual hands. The virtual arms would move according to the hands in a natural way by using inverse kinematics. Inverse kinematics is the computing process of rendering movements, i.e. the rotation of joints, based on an end-effector. The end-effector, or rather target, was in this case the hand controllers' position, which was mapped to the hand. When the hand would move, the rotation of shoulder, upper arm, and under arm would change accordingly, simulating the user's natural movement of these. The virtual avatar consists of mesh and skeleton. The mesh is the form of the body and what users can see, whereas the skeleton is the model of connected joints (Image 9) that will move the avatar's body parts when rotated.

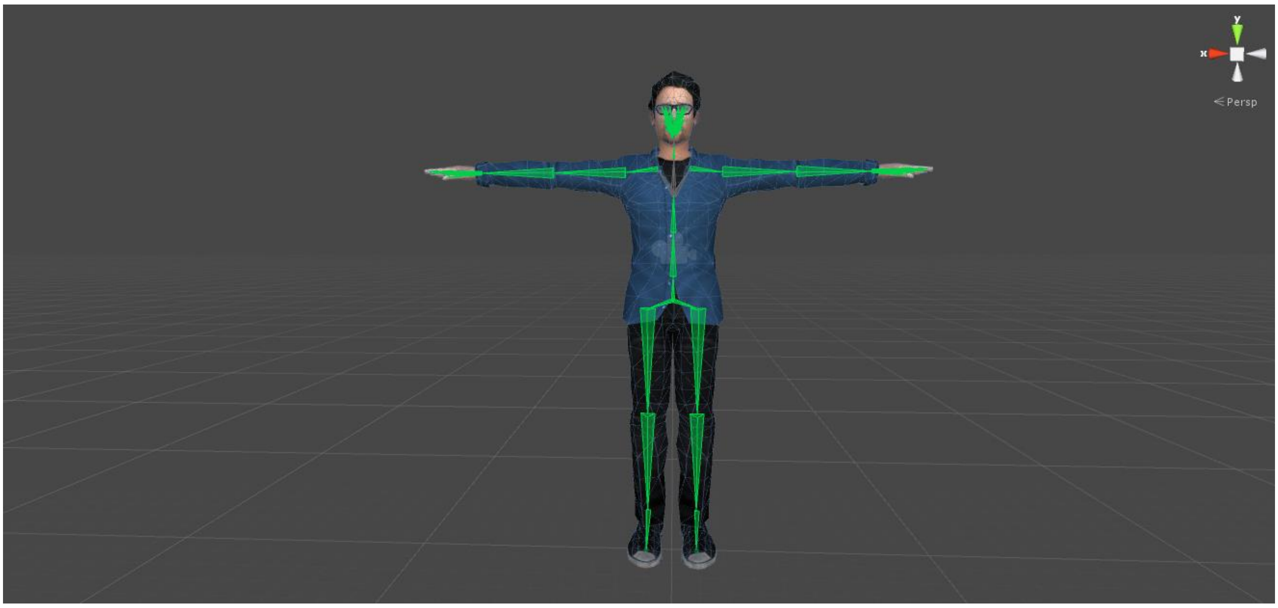

Image 9: The virtual avatar and its skeleton

Image 10: The virtual arm moving naturally according to the target (white box) through inverse kinematics

5.6 Post Test Questionnaire

Following the test, participants would continue to a questionnaire. The virtual screen in front up them would “turn on”, and the questions would appear there. Participants could navigate between questions using the triggers on the hand controllers, and could change their ratings up until continuing to the next test/condition.

To enforce body-ownership and for easier navigation, virtual hand controllers were included in the scene and attached to the virtual avatar’s hands. The hand controllers’ button touches were mapped to the virtual finger positions. Thus participants could see what buttons they were currently touching, which would avoid confusion, should they lose their frame of reference.

To further ease the navigation and to avoid frustration and participants forgetting what buttons did what, explanation of how to use the controllers were explained on the screen. The instruction would describe purpose and use of the button, and refer to the buttons through color coding.

The questionnaire started with acquiring participants’ perception of tap distribution. On the screen, a picture of the virtual arm would appear with an semi-transparent grid overlaid. The grid consisted of 5x20 text fields, placed in a two-dimensional array. Using the controller's thumb stick, participants would navigate to the areas they had perceived taps. However, due to the signal from the thumb stick, which will continuously read as "1" (meaning on) in each frame, the movement between text boxes had to be restricted, as a even a fraction of second moving the thumb stick up, would result in many box jumps, instead of just one. To restrict the movement, a delay of 200ms would be initiated whenever the thumb stick movement returned true (see Code snippet 3)

```
grid[x, y].GetComponent<Image>().color = on_color;
if (up)
            {
                if (!isRunning)
                {

                    if (x > 0)
                    {
                        grid[prevX, prevY].GetComponent<Image>().color = off_color;
                        x--;
                        StartCoroutine(Delay(pauseTime));
                    }

                    else if (x == 0)
                    {
                        grid[prevX, prevY].GetComponent<Image>().color = off_color;
                        x = maxX - 1;
                        StartCoroutine(Delay(pauseTime));
                    }
                }
            }


IEnumerator Delay(float seconds)
    {
        isRunning = true;
        yield return new WaitForSeconds(seconds);
        isRunning = false;
    }
```

Code snippet 3: Navigation between boxes in the grid was slowed through delay

To mark the square/area, right-hand buttons were used to increment and decrement the mark integer. These same buttons where used in the rest of the questions, where participants would rate on a scale of 0-6 (7- point Likert scale).

The answers from the questionnaire were saved into a text file, also containing name of the condition and in what order conditions had been received.

6. TESTING

Following the method described in section 3, two separate tests were conducted. The first test, a preliminary test, was focused on the effect of frequency and distance variables to elicit the CRI. This test would determine which of the 6 combinations (excluding the control condition), would be used in the main test. The main test was focused on answering the final problem statement (see section 2.3), and would attempt to transfer CRI into VR, in effort to see the effect of the illusion in a rendered environment. The following sections will examine and analyze results from the two tests.

6.1 Pre-test/CRI without visuals

A total of 16 participants took part in the preliminary test (6 women and 10 men), aged 25 to 28. Prior to the test, participants were introduced to the procedure through a training session; the training session consisted of a single run-through (without vibrotactile feedback) of the test, and explanation of the questionnaire. Participants were verbally instructed how to navigate and use to the controllers for their responses. All participants were asked to pay attention their arm during the loop sequence, and that the sequence would keep looping until they would continue to the questionnaire with a button-click at their own initiation.

Once the training session was over, and the participant felt comfortable to proceed, they were briefly blindfolded while the tactile display was put on their arm, after which headphones were placed over the ears, and the test session would begin. The test consisted of 7 conditions in a pseudo-randomized order for counterbalance.

Following the pre-existing measure on distribution of perceived stimuli, i.e. the location and frequency of perceived taps on the arm, results were to be analyzed, based on the density and spread of markings (Bremer, et al., 1977). However, the study by Bremer involved only a total of 9 taps spread across 3 points of stimuli, which allowed for categorization of results into following three groups:

1) No saltation (i.e. only 3 points of stimuli had been marked)
2) Some saltation (points of stimuli spread beyond 3 points, but remained in 3 distinctive groups)
3) Full saltation (points of stimuli had spread extensively).

Due to the increased amount of points of stimuli and the varying ISF, it would be impractical to implement same categorization, as this would skew the results in favor of the condition with more points of stimuli. To imitate the method of Bremer (1977), rather than categorizing the markings into weighed groups, the distribution of markings was measured and compared between conditions. The total number of marking weighed against the total area covered by the markings (from first to last mark) would represent the distribution fraction. To measure fraction of distance, i.e. the spread of the markings, the distance of the total covered area weighed against the actual distance between first and last PoS. Performing this comparison, allowed for an estimated categorization that will determine to what degree saltation has occurred in a similar fashion to Bremer's method.

6.1.1 Linear

Results from the questionnaire on the seven conditions are summarized in Figure 10 through Figure 13, where medians, quartile ranges and outliers are presented. Ratings are considered outliers if they lie outside the interquartile range x 1.5 from the nearest quartile edge. Due to the distribution of the markings' data, and the ordinal nature of Likert scale data (from ratings on compellingness and movement), nonparametric procedures were considered appropriate for statistical analysis of the data. The Friedman test was performed to compare ratings from each question. In the case of a significant effect (α=0.05), the Wilcoxon signed-rank test was performed for post-hoc analysis.

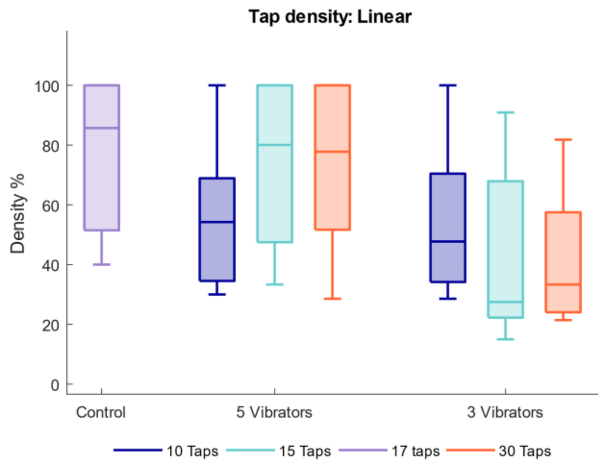

Figure 10: Boxplot of the density percentage of stimuli point markings from the linear array test (p= 0.0319)

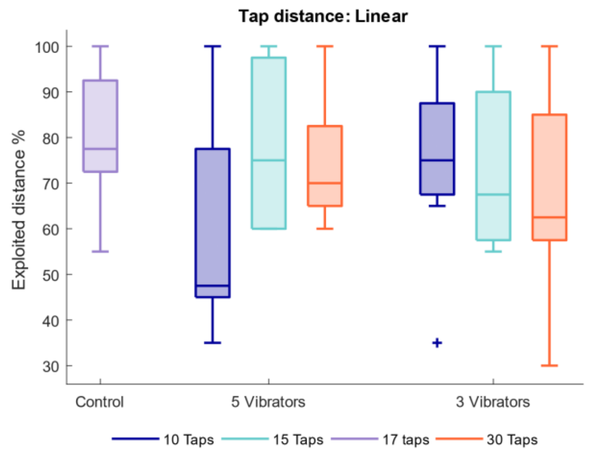

Figure 11: Boxplot of the spread of stimuli point markings from the Linear array test (p= 0.0738)

Significant effects were found in the density of taps between conditions. The Wilcoxon test revealed that condition V3T30 had a significantly lower density than condition V5T15 (p= 0.016) and V5T30 (p= 0.008). As seen in the boxplots (Figure 10), the conditions providing taps across only 3 PoS had in general a lower density than those of 5 PoS. In many cases participants experienced no saltation, meaning only 3 PoS was experienced (10 conditions across 6 participants). Conditions of 5 PoS with 15 and 30 taps performed best, and density was close to the control condition.

In regard to the total distance covered by the markings, condition V5T10 and V3T30 performed the worst, as seen in Figure 11. The distance covered by marks was very spread amongst participants, going down to only 33% (i.e. a distance covering only 5 points). Condition V5T15 performed the best with the highest median and majority of participants reporting wider spread of points.

Comparing the results from distance and density, it is clear that conditions of 3 stimuli points performed worst, as the distance between points was great and the density low, meaning that marking were placed in distinct groups spread wide between, suggesting that little to no saltation occurred in these. Condition V5T15 and V5T30 (along with the control condition) had best performance as their densities were high as well as the spread, indicating the marking were distributed uniformly and wide, thus saltation occurred in these.

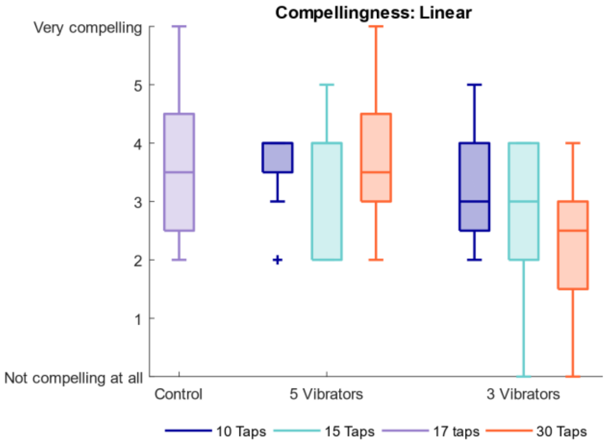

Figure 12: Boxplots of ratings on compellingness of the illusion of movement across the arm for the linear array of vibrotactile stimuli (p= 0.366)

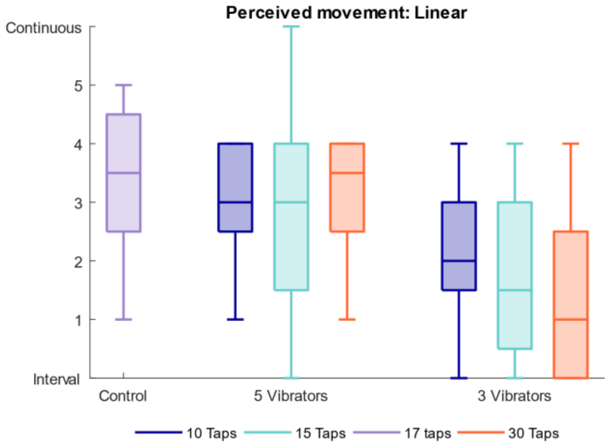

Figure 13: Boxplots of ratings on perceived movement of the vibrotactile stimuli for the linear array (p= 0.2318)

In regards to compellingness of the experience of motion across the arm, no significant difference was found. However, also here, conditions of 3 PoS were rated noticeably lower than those of 5 PoS. Moreover, 5 PoS was found to be smoother in the movement than those of 3 PoS.

For the perceived form of path from the stimuli, seen in Figure 14, almost all participants agreed to having experienced a linear path of motion (only 1 person experienced nonlinear motion in 2 conditions). Overall the 5 PoS had best performance in regards to ISF, where 15 and 30 taps were favorable as it resulted in a bigger spread, thus a higher degree of saltation, perceived in its intended path.

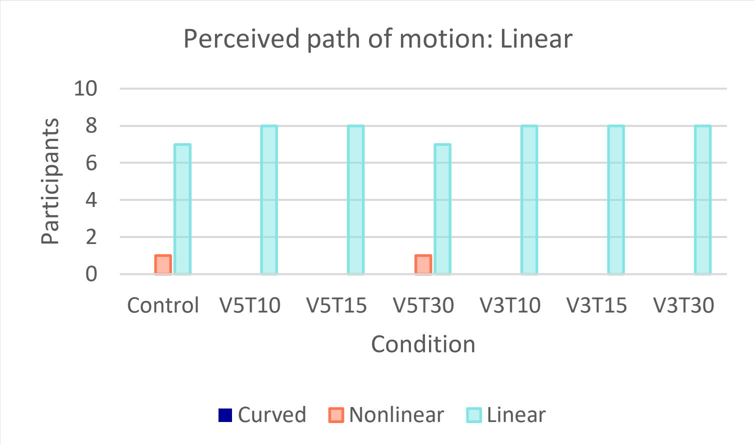

Figure 14: Histogram on perceived paths from vibrotactile feedback based on markings in grid

6.1.2 Curvilinear

Significant differences were also found in distributions and distance fractions from tests with curved array of vibrotactile stimuli (Figure 15 and Figure 16). The density of V3T15 was significantly lower than in the control (p= 0.039), V5T15 (p= 0.008) and V5T30 (p= 0.031), and V3T30 was also significantly lower than

V5T15 (p= 0.016) and V5T30 (p= 0.023). These results show both the 3 PoS conditions performed significantly worse than 5 PoS, and that V5T10 performed the worse of the 5 PoS conditions. In regard to distance covered by marks, also here the 3 PoS had worst performance. V3T30 covered a significantly larger distance than V5T10 (p= 0.031), V5T30 (p= 0.031) and V3T10 (p= 0.017), however, compared to its low density, this indicates concentration of marks in groups with large distances between (as also seen in linear test group), meaning no saltation (6 conditions of 3 PoS across 4 participants reported experiencing no saltation). Condition V5T15 reported the biggest distance between all conditions, which coupled with its higher density, also suggests that marks were evenly distributed across a large area. As with the linear test group, V5T10 performed worst of the 5 PoS conditions.

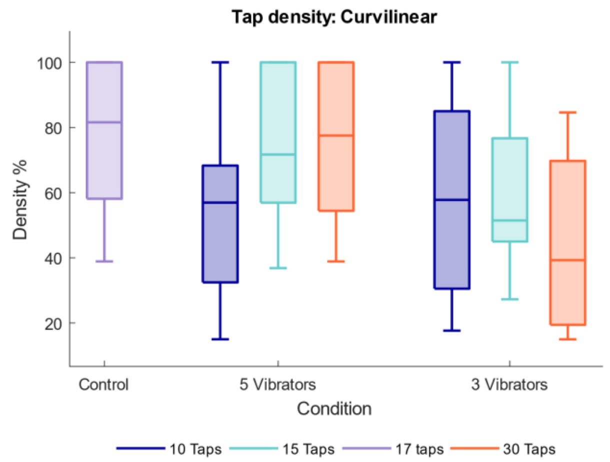

Figure 15: Boxplot of the density percentage of stimuli point markings from the curvilinear array test (p= 0.005)

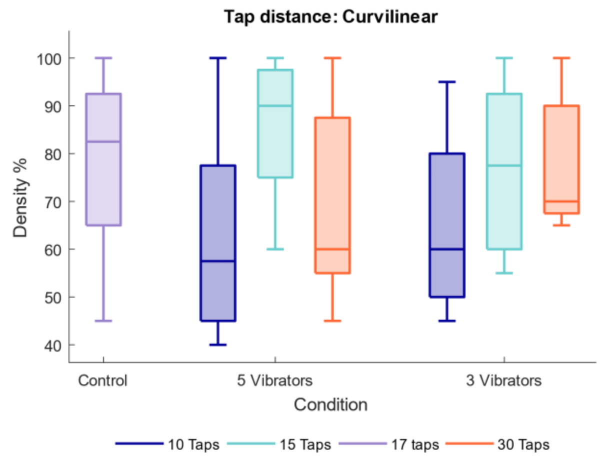

Figure 16: Boxplot of the spread of stimuli point markings from the curvilinear array test (p= 0.0049)

As with the linear test group, no significant differences were found in compellingness and smoothness between conditions. The control condition rendered a more compelling experience, but there was no distinguished difference between 5 PoS conditions (Figure 17). It is evident that V3T30 resulted in the least compelling illusion of motion, and was mostly perceived to be the least smooth in movement (Figure 18).

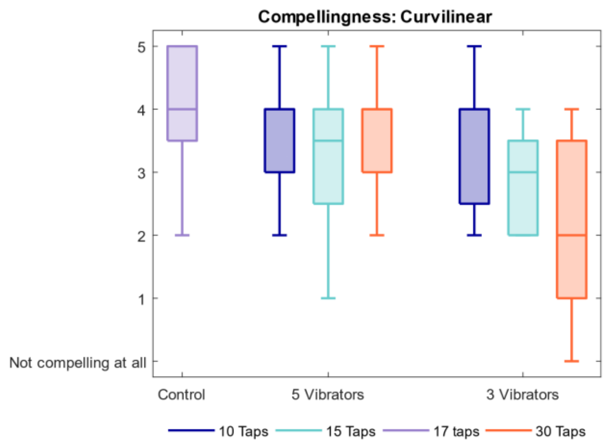

Figure 17: Boxplots of ratings on compellingness of the illusion of movement across the arm for the curvilinear array of vibrotactile stimuli (p= 0.132)

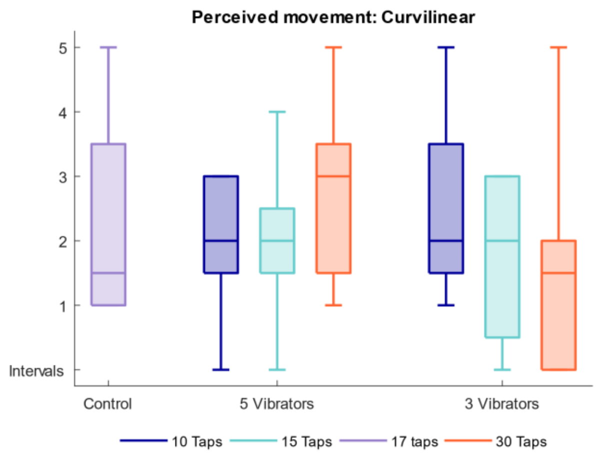

Figure 18: Boxplots of ratings on perceived movement of the vibrotactile stimuli for the curvilinear array (p= 0.522)

The perception of a curvilinear path from the vibrations was less successful than the linear test group, as seen in Figure 19. The majority of participants in the 3 PoS conditions reported linear and nonlinear paths of motion (19 of 24 cases), and only 2 participants marked a curved path in 2-3 conditions. However, in the 5 PoS conditions, majority of participants agreed to a curvilinear movement. Here, majority (18 of 24) reported a curvilinear path of movement perceived across their arms.

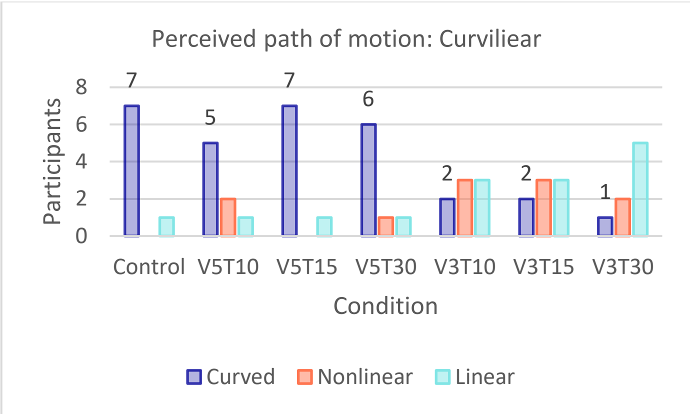

Figure 19:Histogram of perceived motion from marking categorized into curved, nonlinear and linear paths

6.1.3 Linear vs. Curvilinear

In an effort to find the best performance, and to test how the CRI performs on a curvilinear path, it is relevant to compare results from the test groups. To evaluate the groups, the nonparametric Wilcoxon rank sum test (also known as the Mann Whitney U-test) was used on paired conditions between groups.

No significant effect was found, and when looking at the comparisons of boxplots in Figure 20 and Figure 21, results also seem similar. However, curvilinear did perform slightly better than linear in 3PoS groups in terms of both density and distance.

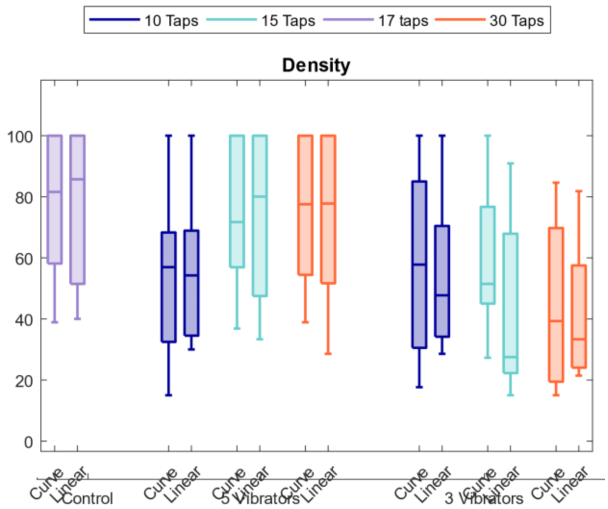

Figure 20: Comparison of conditions between curvilinear and linear test groups on tap density

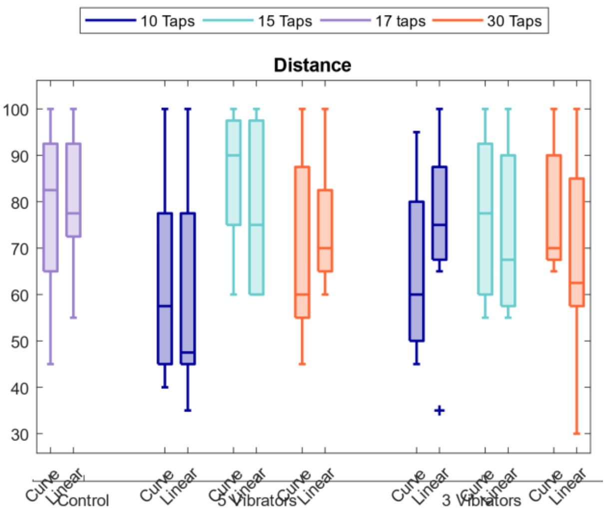

Figure 21: Comparison of conditions between curvilinear and linear test groups on tap distance

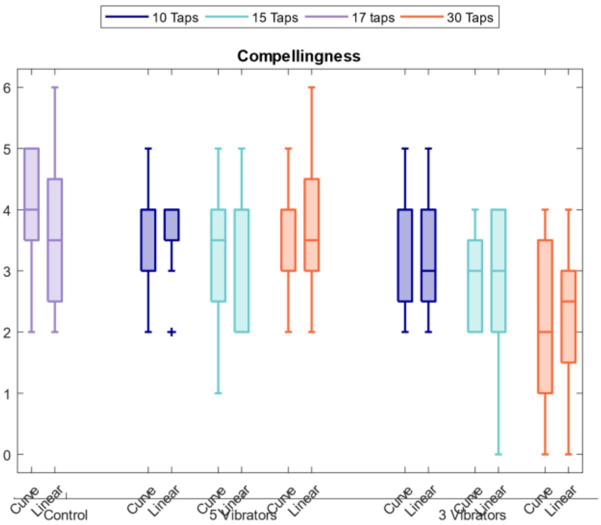

Figure 22: Comparison of conditions between curvilinear and linear test groups on compellingness of illusion

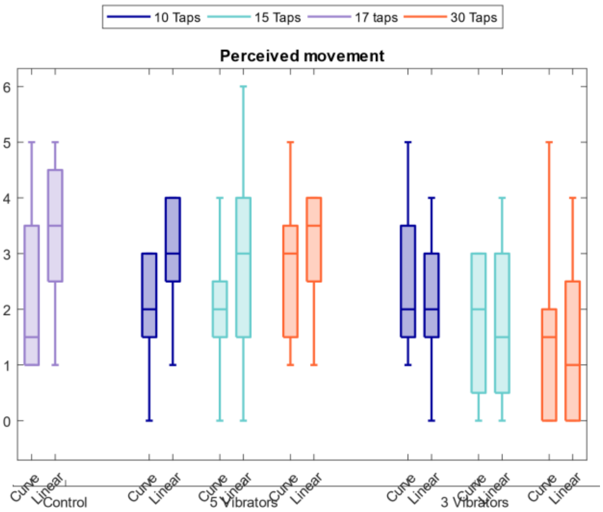

Figure 23: Comparison of conditions between curvilinear and linear test groups on perceived movement

6.1.4 Discussion

Results from the pre-tests show that the CRI is strongly affected by the vibrotactile stimuli. While some degree of saltation did occur for all conditions, some variables excelled more in terms of density and covered tap distance. Conditions V5T15, V5T30 and V3T10 had best performance, where distribution and distance were high, which suggest that saltation occurred. Condition V5T10 and V3T30 had worse performance; for V3T30 where distribution of taps was low and distance was high for both linear and curvilinear test groups, taps were perceived in clusters, and it seem as some anchoring occurred for this condition. This anchoring can also explain the low ratings in compellingness for this condition, and its high ratings for interval movement. V5T10, however, had low density and low distance, meaning that taps appeared in one big group, thus, taps did not distribute well across the arm.

The pre-test also showed that curvilinear CRI can be achieved, however, in the unimodal case where only vibrations provide feedback, 3 PoS is not sufficient. It was not possible for participants to distinguish between movement on this few PoS, and only few perceived the movement as curvilinear. However, 5 PoS showed better results in this area; here the majority recognized the curvilinear path, although the number of participants who correctly perceived the path to be curved is inferior to the linear test group.

No significant difference was found between curvilinear and linear test groups; the curvilinear path was well-received and recognized for 5 PoS, meaning that CRI is not limited to linear paths only.

The V5T15 condition received best ratings in both test groups; it did the best job in distribution taps evenly and far, creating the most compelling illusions, and also had highest motion path recognition. The control condition and V5T15 rendered similar responses across all questions, although the control condition did perform best. As the purpose of the control condition was to gather ratings for "true" saltation for comparisons, it is fair to say that V5T15 had best performance amongst conditions.

Based on the result on the pre-test, the main VR test will use these parameters for its vibrotactile stimuli. However, as the pre-test was a unimodal scenario, and in the interest of testing minimum requirements for CRI to occur in, the main test will also perform its test on the V3T15. When visuals are coupled with the vibrations and the experience becomes multimodal and engaging, the 3PoS condition may perform better than in this pre-test. And peraps it will prove to be equally good as V5T15 in the rendered environment.

6.2 Main test/ CRI in VR

Based in results in the pre-test, the main test will create the CRI in VR through 5PoS of each 3ISF, and 3PoS with 5ISF. This VR test follows description in section **Fejl! Henvisningskilde ikke fundet.**, and the following will account for the data gathered in the main test for both linear and curvilinear.

A total of 30 people (12 women and 18 men) participated in the main test, aged 26-32. As with the pre-test, participants were introduced to the navigation with hand controllers via a training run-through of a test session. Participants were instructed to look at the virtual ball move along their arm and notice how the movement felt. Once they felt comfortable with the use of the hand controllers and the navigation, the head-mounted display was put on with black visuals, after which the tactile display was placed on the left arm. The virtual game session was started, and participants could explore the visual scene before setting off the ball animation at their own choice, through a button-click. Like the pre-test, the vibrations – and in this case, concurrently with the virtual ball moving - would loop the sequence continuously until participants chose to continue to the questionnaire. The order of visuals/vibration-combination sequences were pseudo-randomized for counterbalance, to avoid any possible biases. As described in **Fejl! Henvisningskilde ikke fundet.** participants were presented 4 visuals combined with 2 different vibrations of either 3 PoS or 5 PoS, a total of 8 conditions.

Like the pre-test, the responses from marks in the grid were measured in terms of density and total distance covered by marks (first to last mark). The percentage of density of marks is the fraction of the total distance covered by marks, and distance percentage is measured as fraction of the distance covered over the actual distance of 17.

The Friedman test was performed to compare results, with the Wilcoxon signed-rank test as post-hoc in the case of a significant effect (α=0.05)

6.2.1 Linear

In Figure 24 and Figure 25, results on tap density and distance from markings are summarized in boxplots. No significant effect was found on distance between conditions (p=0.6309), however, a significant difference was found between tap densities between conditions (p=0.003). As seen in Figure 24 visual conditions without jumps between points performed better in terms of density than those with jumps.

For 3PoS, the condition L3N were significantly more uniformly distributed than C3J (p=0.047), and performed noticeably better than L3J (p=0.055). The density of C3N also performed better than visuals with jumps (linear p=0.016; curved p=0.016). This same tendency of more equally distribution of taps was repeated for 5PoS, where L5J and C5J had higher density of taps for L5N (p=0.027; p=0.045) and C5N (p=0.016; p=0.039). However, only little differences were found between the distances covered (Figure 25). The pattern of visuals with jumps having less uniformly distributed marks while still covering approximately same distance and majority of participants experiencing taps distributed >50% of the distance, show that some degree of saltation did occur, and that the visual tapping influenced the perception of taps. In the case of visual jumps, the jumps were translated to the perceived sensation of taps. No significant differences were found within the visual conditions.

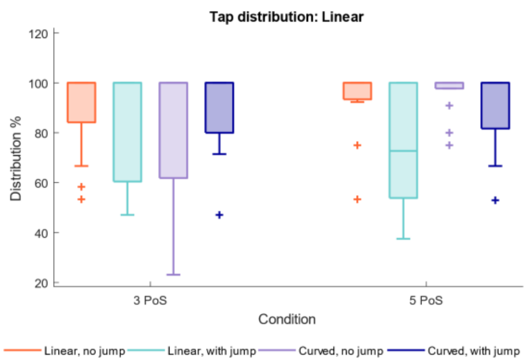

Figure 24: Boxplot of the density percentage of stimuli point markings from the linear array test (p= 0.003)

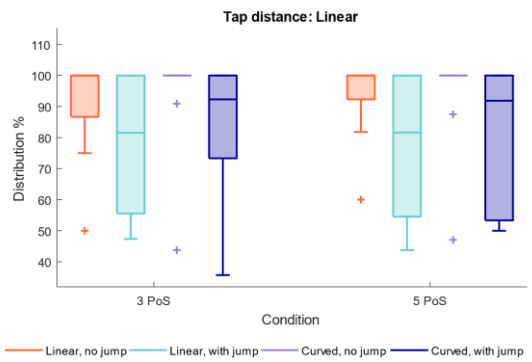

Figure 25: Boxplot of the spread of stimuli point markings from the Linear array test (p=0.6309)

Looking at how the path of vibrations were perceived (Figure 26), the majority of participants' responses matched the current visual feedback they were receiving, regardless of how the path was in reality. The conditions of 3 PoS did perform slightly better here.

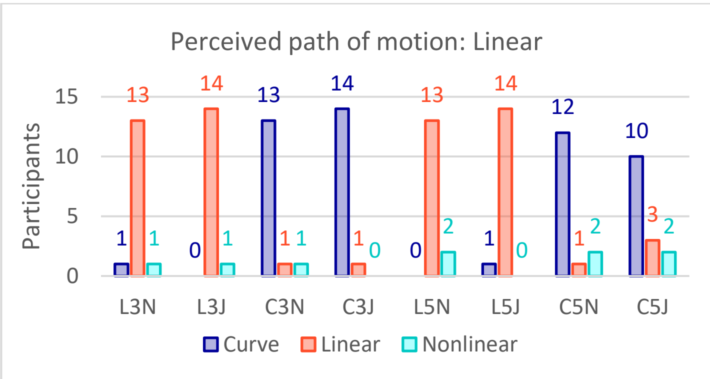

Figure 26: Histogram of perceived path for linear array of vibrations

The visuals of tap movement are also reflected in how smooth the saltation was perceived, as seen in Figure 28. Also here, visuals including animated jumping, were perceived as more interval than continuous. No significant effect was found in compellingness, however, 5 PoS vibrations did yield a general higher level of compellingness, and especially C5J rendered to most compelling illusion of movement.

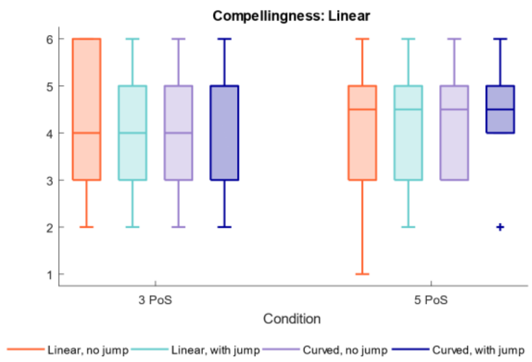

Figure 27: Boxplots of ratings on compellingness of the illusion of movement across the arm for the linear array of vibrotactile stimuli (p= 0.944)

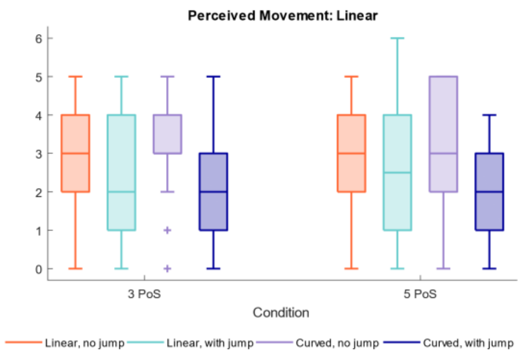

Figure 28: Boxplots of ratings on perceived movement of the vibrotactile stimuli for the curvilinear array (p= 0.256)

Regarding body-ownership, the majority of participants did agree to have experienced some level of body-ownership (>3), as seen in Figure 29. No significant differences were found between conditions, and visuals seemingly did not affect the body-ownership.

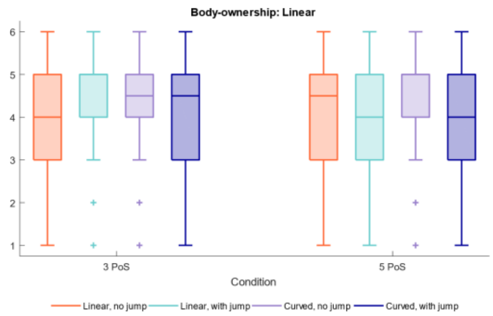

Figure 29: Boxplots of ratings on body-ownership for the virtual arms for the linear array (p= 0.3281)

6.2.2 Curvilinear

Boxplots on tap density and distance can be seen in Figure 30 and Figure 31. As the linear test group, the visual motion of the ball affected the density, yet not the covered distance, again, implying that visual jumping would affect the distribution of tapping. However, only the 5 PoS group yielded a significant effect between conditions, whereas 3 PoS seem more similar in its densities. For 5PoS, L5J performed worse than all other conditions within the vibrational group, and was perceived denser and less spread in its taps; L5J (p=0.014); C5N (p=0.004); C5J (p=0.008).

Between vibrotactile conditions, L5J performed worse than its 3 PoS counterpart L3J (p=0.008) and C3J. However, the C5N performed better than its 3PoS counterpart C3N (p=0.031).

No significant main effect was found between conditions on covered distance (p=0.221), however, C3J and C5J did tend to spread more than C3N and C5N. In terms of distance, 5 PoS with linear visuals performed the best of all conditions.

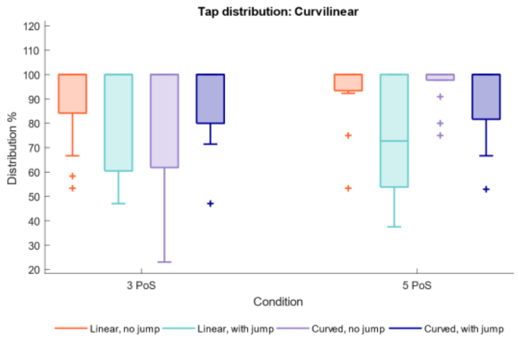

Figure 30: Boxplot of the density percentage of stimuli point markings from the curvilinear array test (p=0.003)

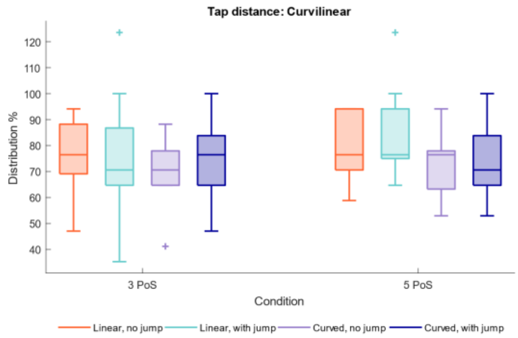

Figure 31: Boxplot of the spread of stimuli point markings from the curvilinear array test (p=0.221)

However, looking at the categorized paths participants had perceived in Figure 32, based on their markings, the rendered experience was a mix between what the visuals informed and the actual tactile stimuli. In visual conditions with curved motion, majority of participants agreed to have experienced curved motion. However, for linear visuals, the responses there was more confusion; participants split, and only approx. 47-60% had perceived a linear motion across all linear conditions.

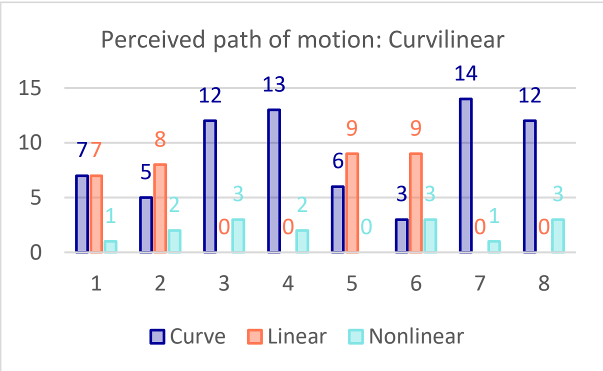

Figure 32: Histogram of categorized perceived path for curvilinear array of vibrations

Regarding compellingness (Figure 33), 5 PoS conditions rendered a more convincing illusion in general, though no significant effect was found. In 3 PoS groups 25-30% of participants actually reported the experience was not compelling (ratings below 3).

As in the linear test group, the smooth visuals were matched by the perceived movement of the ball; in conditions without jump animations, the movement was rated as being more continuous, as seen in Figure 34.

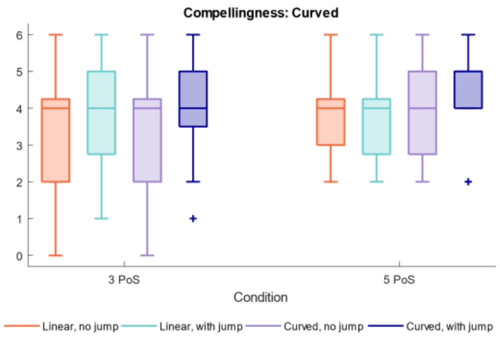

Figure 33: Boxplots of ratings on compellingness of the illusion of movement across the arm for the curvilinear array of vibrotactile stimuli (p= 0.307)

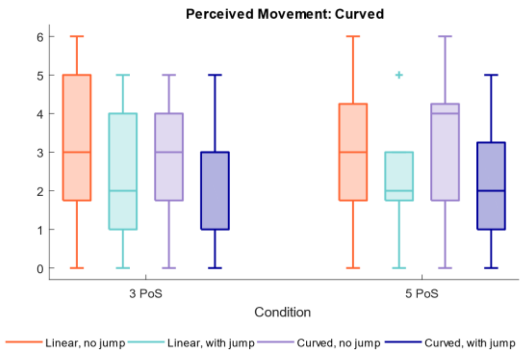

Figure 34: Boxplots of ratings on perceived movement of the vibrotactile stimuli for the curvilinear array (p=0.1614)

No significant difference was found on body-ownership between conditions; in all conditions, majority of participants agreed having some level of body-ownership (ratings above 3).

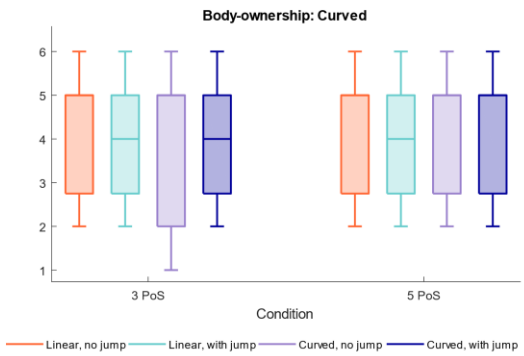

Figure 35: Body-ownership ratings for curvilinear vibrotactile array (p=0.513)

6.2.3 Curvilinear vs. linear

To test the differences between curvilinear and linear group tests, the Wilcoxon rank sum test was performed on matched condition, however no significant effect was found.

In Figure 36 boxplots from both test groups are paired up by conditions. In visual conditions without jumps, the 5PoS vibrotactile stimuli rendered the most uniformly distributed perception of taps. Saltation did occur for all conditions; however, saltation did fail in 2 cases for 2 participants (curvilinear L5J 6 marks, curvilinear C3N 3 marks). The distribution of taps in visual conditions with animated jumps between taps resulted in less uniform distribution, which in majority of cases meant participants had marked a gap between taps, i.e. even ratio between taps and gaps (for linear array 75% (21 of 28) and curvilinear 67% (14 of 21) conditions with visual jumps and distribution between 50% and 100%). So, it is debatable whether the illusion was less successful in these cases, as saltation did occur and was congruent with the visual feedback.

In terms of distance (Figure 37), the 5 PoS conditions also performed better in general, however, there was distinctive difference between the vibrotactile groups. No significant difference between body-ownership, compellingness, and smoothness of movement was found.

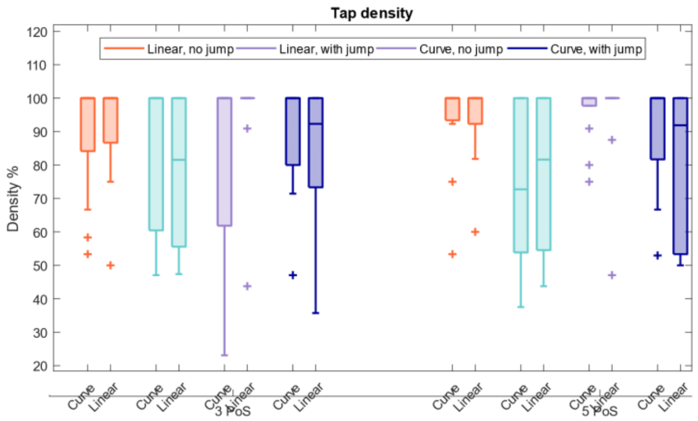

Figure 36: Comparison of conditions between curvilinear and linear test groups on tap density

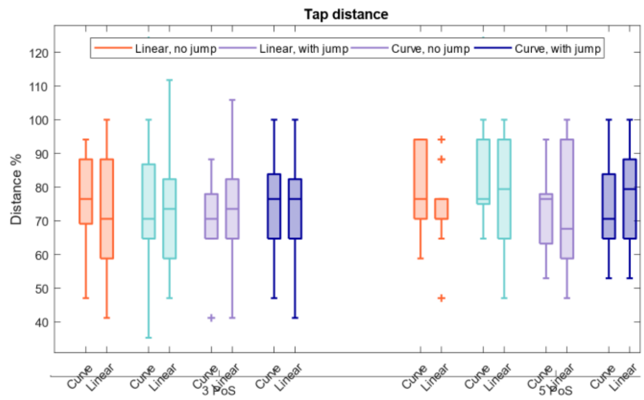

Figure 37: Comparison of conditions between curvilinear and linear test groups on tap distance

While the differences between 3 PoS and 5 PoS were small, and saltation was successful in the majority of cases, there was a substantial difference in the perceived paths of movement. In Figure 38, a comparison on perceived paths between the curvilinear and linear test groups can be seen, showing how many participants perceived same path as what had been visually demonstrated. Here, the linear vibrotactile array proves to be more diverse in its virtual direction, as the majority of participants were able to perceive both curvilinear and linear paths. The curvilinear test group struggled more in generating a linear illusion, and was almost equally successful in creating a curvilinear sensation as the linear test group. Surprisingly, the 3 PoS linear test group performed better in its curvilinear imitation than the corresponding 5 PoS conditions.

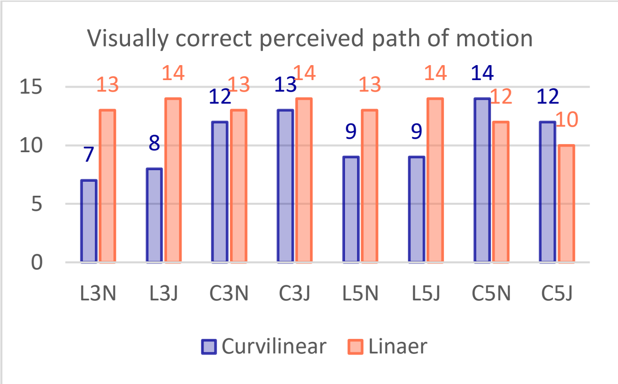

Figure 38: Comparison of perceived paths congruent with the current visual, based on markings between curvilinear and linear test groups

6.2.4 Discussion

The test results showed that CRI can occur regardless of the vibrotactile path, as both linear and curvilinear test group experienced compelling illusions of saltation. The pre-test established that a 5 PoS of 3 taps would create the strongest illusion in terms of tap distribution, covered distance and compellingness, and that a 5PoS was necessary to create a curvilinear saltation.

However, when coupled with visual feedback, the cutaneous feedback became a lesser determining factor, as the visuals played a dominant role in tap distribution and path. The visual feedback enhanced the illusion to the point, where 3 PoS yielded a similar strength of saltation. With visual feedback, taps were perceived to be more uniformly distributed compared to the pre-test. Interestingly, the 3PoS that failed to simulate a curvilinear path in the pre-test, succeeded in doing so when accompanied by visual feedback.

The vibrotactile conditions were coupled with four different visual feedback, and the visual feedback would be incongruent to the tactile feedback in half of these conditions. However, the CRI was somewhat unaffected by this; while the illusion tended to be slightly stronger when visuotactile feedback was congruent, the mismatch was for the majority not a noticeable factor; rather, the visuals will start to modulate the perception of taps in accordance to the current visual stimuli. In condition where the ball would jump, participants would report less marks, yet still distributed over the same distance as the continuous movement. And as described in 6.2.3, the majority of participants who reported change in tap distribution between jump and no-jump conditions, still reported uniformly distribution of marks, but with a gap between marks, just like the visual jumps. Moreover, the visuals also influence how the movement is perceived (in a continuous-interval continuum); visuals jumps will result in a stronger sensation of jumps, whereas no visual jumps will render a continuous/smooth sensation of movement.

As mentioned, the visuals also modulated the perceived path of taps, and is unaffected by incongruency between the real, vibrotactile stimuli and the visuals. Thus a curvilinear tactile path may be perceived as linear, if the visuals informs so. However, a linear tactile path performed better than curvilinear in the visuotactile manipulation; as seen in the reported paths of marks, the linear array of vibrators had more success in generating a curvilinear sensation, then the curvilinear array had in creating a linear sensation.

Interestingly, while the pre-test found significant differences between 3PoS and 5PoS conditions, there was no significant effect between 5PoS and 3PoS of 15 taps when coupled with visuals. The 3PoS responses improved due to visuals, however, 5PoS still proved to create a stronger illusion, though not of significant effect.

7. DISCUSSION

From the initial problem statement, "*How will a virtual reality simulation affect the cutaneous rabbit illusion?*", it was relevant to elaborate on the cutaneous system, the CRI, and how others had successfully elicited this illusion. The research led to the method of assessing the CRI with subjective measures.

Presence is a concept highly connected to VR, and thus, this was briefly touched upon, as a natural opening to the discussion on body-ownership. Body-ownership was a relevant topic to visit, as the CRI has been demonstrated on participants' physical bodies, and therefore is was decided that there should be a virtual body to represent these physical bodies. It was furthermore decided that the virtual body should correspond somewhat to the body of the participants, as high realism would enhance body-ownership. The body should match the body schema and the body image. Assessing body-ownership is most often done by self-reported ratings, as this is a subjective emotion. It can also be assessed by observing behavioural realism, by e.g. implementing a threat to see whether this threat will elicit a naturalistic response. It was, however, decided that the assessment of body-ownership would be exclusively by self-reported ratings.

It was decided that the main focus of the VR simulation should be on visuals. The field of interest in terms of the CRI, was the saltation that would occur, as this might be beneficial to VR applications using tactile displays, as this might reduce the hardware needed. This led to the final problem statement, "*How will visual feedback in a virtual reality simulation affect the perception of saltation of linear and curvilinear vibrotactile stimuli?*"

Current literature showed that a high ISF would result in taps anchoring rather than wandering, however, no specific parameters were given in this context. Moreover, in terms of BSD, while the CRI has been shown to wander over big distances (from hand to shoulder), no details on how BSD affects the illusion, and its compellingness, was made clear. This led to the pre-test that would determine these parameters, before continuing to the main VR test.

The testing would consist of first a pre-test, to establish the appropriate BSD and total ISF. This led to a design of 7 conditions (including a control condition), which was to be performed with both linear and curvilinear vibrotactile feedback from the tactile display, between groups.

The pre-test results established that some degree (including both weak and strong) of illusions of saltation may occur regardless of ISF and BSD. However, if the ISF is too high or too low, as was the case for V5T10 and V3T30, the illusion is broken, as anchoring will begin. This means that the taps will cluster in groups, most likely at the PoS, and no saltation will occur.

Results also showed that a shorter BSD will enhance the CRI and produce a more compelling illusion. In regard to using CRI for a curvilinear path, the pre-test responses showed that 3PoS is not sufficient in simulating a curvilinear motion. 5PoS with 3 ISF proved to be more appropriate for such a task, as the number of stimuli points were necessary is creating a curvilinear path, while avoiding anchoring of the stimuli. In effort to still reduce the number of vibrators, it was of interest to test if 3PoS could prove sufficient when coupled with visuals. As such a 3PoS with 5 ISF were included in the main VR test as well.

The results showed that the CRI can occur regardless of whether the vibrotactile feedback is in a linear or curvilinear path. The pre-test showed that saltation will occur in the majority of cases, but that a 5 PoS is preferable, as this is more prominent in creating saltation in all cases, where 3 PoS did fail in some cases. Unaccompanied by visuals, the 3 PoS will not create a curved, or even a non-linear sensation. In this instance, the 5 PoS is more successful in creating a curvilinear motion. Furthermore, 5 PoS will render a more compelling illusion, whereas 3 PoS might fail, and did so on approximately 50% of all cases.

In the VR test, results showed that visuals did affect the CRI to the point where possibly any shape of path can be generated using a linear array. The visually-dependent effect of the CRI was evident, as the visual feedback both controlled the path of vibrotactile stimuli as well as its distribution of taps; visual jumps would cause a larger distance between marks, and continuous visual path would create a smoother perception of the virtual object's movement. No significant effect was found between the group of tactile feedback, meaning that 5PoS will not give any significant effect, and that 3PoS was enhanced by visuals to the point that it may be as effective as 5PoS. However, 5PoS will still yield a stronger illusion.

Visuals did affect the CRI to the point where possibly any shape of path can be generated using a linear array, and the distance between vibrotactile stimuli can be stretched further to being 7cm apart and still render a compelling illusion. This is also in agreement with findings from other studies, where the CRI can be successful over large distances. This also goes to show that the illusion can be almost just as powerful with only few vibrators in use, when accompanied by visuals.

8. CONCLUSION

As this project strove to answer the final problem statement; "*How will visual feedback in a virtual reality simulation affect the perception of saltation of linear and curvilinear vibrotactile stimuli?*", results from testing showed that the CRI can successfully be transferred to VR, and that the visual feedback from the VR setting did have an effect on the perception of saltation, to a degree where the visual sense was powerful enough to create an illusion in terms of the path of the vibrotactile stimuli.

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