Exercise Accessibility for People with Blindness and Visual Impairments: Assessing the Potential of Tongue Interfaces
(Alternative Format Thesis)

Richardson, Mike

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Exercise Accessibility for People with Blindness and Visual Impairments: Assessing the Potential of Tongue Interfaces

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A thesis submitted for the degree of Doctor of Philosophy

University of Bath
Crossmodal Cognition Lab
Department of Psychology

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Declaration of any previous submission of the work

The material presented here for examination for the award of a higher degree by research has / has not been incorporated into a submission for another degree.

Declaration of any authorship

I am the author of this thesis, and the work described therein was carried out by myself personally. Individual chapters are accompanied by an authorship statement indicating my contribution to the work in terms of formulation of ideas, design of methodology, experimental work and presentation of the data in journal format.

Abstract

Regularly participating in sport and exercise is extremely good for health and well-being. However, for people with blindness and visual impairments, access to exercise is restricted compared to others. One promising method for increasing access to exercise is the applied use of novel technological interventions. Specifically, the field of sensory substitution may be able to provide suitable visual assistance for sport and exercise, although sensory substitution devices have not yet been explored for this purpose. The BrainPort is a vision-into-tactile sensory substitution device that converts visual information into electrotactile stimulation on the surface of the tongue and is a popular device in substitution research. Among sensory substitution devices, the BrainPort is perhaps a compelling choice as a visual aid for exercise as it has a good spatial and temporal resolution, and is a stand-alone unit, with a camera mounted on the forehead and integrated processing unit at the back. Yet surprisingly little is known about the tactile capabilities of the tongue and whether people can successfully interpret the kinds of information required for performing sport and exercise through it. This thesis uses psychophysical methods to explore the potential of tongue interfaces, such as the BrainPort, for the purpose of exercise, and additionally, probes aspects of exercise accessibility for people with visual impairments. It finds that tongue interfaces do have a potential for improving access to exercise for people with visual impairments if careful considerations are made. Primarily, the tongue has a limited ability to orientate attention on its surface, therefore, it is easy to overload with tactile information. Furthermore, the findings show that people with visual impairments are willing and able to adopt new technology to aid them in exercise habits and routines. Finally, based on these findings, the thesis proposes the development of a novel artificially intelligent sensory substitution software, designed to aid navigation in rock climbers with visual impairments by directing spatial attention to climbing hold locations, via a tongue interface.

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Introduction

Exercise is a well-known contributor to long-term health and well-being. Alongside regularly eating fruit and vegetables, avoiding drinking alcohol or smoking cigarettes, participating in sport and exercise is a common health-related activity that most people have a general awareness of (Morrow et al., 2004; Myers & Roth, 1997; Pretty et al., 2003). The physical benefits are perhaps the first to come to mind when considering exercise implications to health and well-being. For decades doctors, clinicians, and health professionals have touted the advantages of regular exercise to cardiovascular health (Blair, 1996; Blair et al., 1989; Breslow & Buell, 1960; Morris & Crawford, 1958), decreased risk associated with hypertension (Blair et al., 1991; Myers et al., 2002), decreased risk associated with Type II Diabetes (Sigal et al., 2004; Thomas et al., 2006), and treatment of abnormal lipoprotein levels (Stefanick et al., 1998), to name but a few common health markers. Comprehensive review articles generally conclude that exercise is irrefutably good and can improve the vast majority of peoples' physical health (Janssen & LeBlanc, 2010; Kokkinos, 2012; Warburton et al., 2006; Warburton & Bredin, 2017).

There is also an increasing volume of evidence that would suggest regularly participating in exercise has a positive effect on psychological and neurological health. Exercise seems to play a preventative role in occurrences of common mental illnesses such as depression (Babyak et al., 2000; Cooney et al., 2013), anxiety (Anderson & Shivakumar, 2013; Petruzzello et al., 1991), and perhaps addiction (Lynch et al., 2013). Exercise also induces neurogenesis of the hippocampus (Liu & Nusslock, 2018; Pereira et al., 2007; van Praag et al., 2005), indicating the potential for increases to learning and memory. Accordingly, there is now speculation concerning the potential role exercise may play in slowing brain aging and as a preventative factor against dementia (Lautenschlager et al., 2012). The social benefits of participating in sport are often left out from discussions of health and well-being, but are no less potent, particularly for people with visual impairments (Ilhan et al., 2021). Outdoor walkers report collective enjoyment of the countryside and the facilitation of social networks (Macpherson, 2017), and exercising with others increases the stress-reducing components of exercise (Plante et al., 2001).

However, despite the great many benefits of exercise, many people struggle to exercise sufficiently, to the detriment of their health. For the general population barriers such as cost, available facilities, limited time, and motivation are common (Ebben & Brudzynski, 2008; Myers & Roth, 1997; Tappe et al., 1989). On top of these, people with visual impairments face additional barriers to exercise (Jaarsma et al., 2014). As such, people with visual impairments often suffer with many of the comorbid ailments associated with lack of exercise, for example, weight gain (Crews & Campbell, 2001; Holbrook et al., 2009), depression (Hayman et al., 2007; Ribeiro et al., 2015), hypertension and heart disease (Crews et al., 2017). Participating in sport has many benefits for people with visual impairments. For instance, Goalball players have increased performance in motor fitness assessments, such as balance, hand grip, and flexibility (Çolak et al., 2004). Furthermore, athletes with visual impairments score higher on quality-of-life measures than matched controls (Ilhan et al., 2021). Investigating methods to improve access to exercise for people with blindness and visual impairments could facilitate improvements to lifestyle and autonomous functioning.

The prevalence of blindness and visual impairment is non-trivial, affecting approximately two-million people in the UK (NHS, 2018), and an estimated 285 million globally (Pascolini & Mariotti, 2012), with 36 million meeting the threshold for blindness (Bourne et al., 2017). People rate hypothetical sight loss as the worst affliction that could befall them relative to losing speech, hearing, a limb, or memory (Bourne et al., 2017). Many types of blindness and visual impairment are treatable, but in low-income countries, many do not have sufficient access to healthcare (Burton et al., 2021; Leasher et al., 2019; Wang et al., 2020). In the USA, leading causes of blindness are reported as macular degeneration, glaucoma, cataracts, and diabetic retinopathy (Burton et al., 2021; Leasher et al., 2019; Pelletier et al., 2016; Wang et al., 2020), and in Western Europe the leading causes are cataracts, uncorrected refractive error (impairments that could be corrected by lenses, but have not), macular degeneration, glaucoma, and diabetic retinopathy (Bourne et al., 2014). In the USA and Western Europe where access to healthcare is higher than poorer nations (Collins, 2003), most of these causes of visual impairment are not currently treatable (Bourne et al., 2014; Burton et al., 2021). Fledgling technology, such as retinal implants (da Cruz et al., 2016; Luo & da Cruz, 2016; Weiland et al., 2005), gene therapy (Al-Saikhan, 2013; Sahel & Roska, 2013), and optogenetics (Baker & Flannery, 2018; Pan et al., 2015; Sahel & Roska, 2013), are currently in development and may offer some hints towards treatments in the future. However, these are currently not feasible as a direct treatment for blindness, and it is unlikely that they will be for some time. In the interim, it is crucial that research and healthcare professionals aim to treat the comorbid ailments that often transpire along with vision impairment.

Assistive Technology for Visually Impaired Sport

Technological intervention is a proven method for improving access to exercise, particularly for people with visual impairments (Burkett, 2010; Hersh & Johnson, 2008). At the most basic level, VI tennis, Goalball, and Blind Football all utilise a specialised ball which generates noise as it moves to allow players to spatially construct its location in space (Velten et al., 2014, 2016). Target sports, such as archery and shooting use tactile and audio 'sights' to provide feedback and help align the shot (Allen et al., 2019; Myint et al., 2016; Taylor, 1953). Recently, more experimental applications of technology have been explored to increase access to other sports. A group of researchers developed 'Eyes-free Yoga', a digital exergame that uses a Microsoft Kinect camera to track body position and provide real time feedback for users that were blind or had low vision (Rector et al., 2013). Another group adapted two Nintendo Wii Sports to include extra sensorimotor feedback to its users (Morelli, Foley, & Folmer, 2010; Morelli, Foley, Columna, et al., 2010). Playing music to help orientate slalom kayakers has been explored (Anthierens et al., 2018), as has attaching sound emitters to rock climbing hand holds to help navigation (Ilich, 2008). The possibilities for technologically aided sport are somewhat inexhaustible, particularly if including exercise-games (or exergames), such as Nintendo Wii.

Exergames may be a good proxy for sport and exercise, containing some, but not all the benefits of performing the sport in real life (Mellecker et al., 2013). Presently, much of the newly developed accessible technology either relies on exergaming (Boffoli et al., 2011; Morelli, Foley, & Folmer, 2010; Morelli, Foley, Columna, et al., 2010; Rector et al., 2013), or manipulation of the environment (or objects in the sporting environment) to provide an extra level of feedback to a different sensory modality (Ilich, 2008; Kirtland et al., 2013; Velten et al., 2014, 2016). In the examples above, this comes in the form of placing sound emitting devices at points of interest in the sporting environment (i.e., at climbing hold locations, or, at slalom gates). While these methods have demonstrated promising results, they lack transferability. In the climbing example, a sound emitter would need to be placed at each climbing hold for many different routes, which would entail a support climber placing the emitters beforehand, and then removing them afterwards. These methods of technological assistance are targeted and specific (and therefore, effective), however their specificity makes them restrictive.

A more general method of technological vision assistance can be found in the field of sensory substitution. Sensory substitution aims to create general purpose vision-assistive devices that transform downscaled visual information to the user via a different sensory modality. Sensory substitution has offered some promising results in the laboratory and under training regimes (Grant et al., 2016, 2018; Striem-Amit et al., 2012), in real life use cases (Ward & Meijer, 2010), and for motor tasks such as navigation (Chebat et al., 2011, 2015; Jicol et al., 2020; Johnson & Higgins, 2006; Kolarik et al., 2017). However, these devices are yet to be widely adopted for people with visual impairments (Gori et al., 2016; Kristjánsson et al., 2016; Maidenbaum, Abboud, et al., 2014). Furthermore, research has not applied the use of sensory substitution to sporting and exercise activities (van Breda et al., 2017), in part, perhaps due to sport and exercise offering a higher-level challenge; indeed, why learn to run, before walking has been successfully mastered by sensory substitution device (SSD) users? In order to consider potential applications of substitution for sport, it would first be useful to briefly review the previous and current uses of sensory substitution to gain an understanding of available technology and crossmodal interfaces. This is also important knowledge to build from, as to effectively highlight possible reasons why SSDs have not become widely adopted for general use, or exercise uses.

Sensory Substitution for Visual Impairments

Sensory substitution was popularised by Paul Bach-y-Rita in the 1960s with his 'Tactile Vision Sensory Substitution' (TVSS) device; a machine that used vibrating solenoids to print an image captured by a television camera, into the back of participants, while sitting in a specially adapted dentist chair (Bach-y-Rita et al., 1969). While this seminal device was unwieldly, it proved an interesting concept that has remained at the core of sensory substitution research: visual information can be presented to, and perceived through, other sensory modalities. SSDs are typically formed of three main components including: a sensor, a processing unit, and an interface. For many SSDs the sensor takes the form of a camera if the device is designed to substitute vision (Abboud et al., 2014; Danilov & Tyler, 2005; Hamilton-Fletcher et al., 2021a; Meijer, 1992). However, devices exist to transform information between a large variety of sensory modalities, including sound-into-touch (Novich & Eagleman, 2014), vestibular-into-touch (Danilov et al., 2007), touch-into-sound (Lanzetta et al., 2004; Lundborg et al., 1999), and modalities that the human body does not normally have access to, such as thermoimaging-into-sound (Hamilton-Fletcher et al., 2021a), and magnetoreception-into-touch (Nagel et al., 2005).

The versatility of sensory substitution relies on brain neuroplasticity, that is, the brain's ability to create and reorganise synaptic connections in response to new information or environmental change. Specifically, areas of the visual cortex can be activated by sensory substitution. For example, the extrastriate body area (EBA) can be activated via sensory substitution after training in participants with congenital blindness, and therefore, no prior visual experience of body shape (Striem-Amit & Amedi, 2014). Furthermore, the lateral-occipital tactile-visual area (LOtv) can also be activated by a SSD, despite this area normally responding to only visual and haptic object information (Amedi et al., 2007). In contrast, the LOtv does not show activation in response to random auditory soundscapes, associated object sounds (for example, recognising a dog by a bark), or masked objects; the LOtv must be predominately activated by shape information, which, without the use of sensory substitution, would be exceedingly difficult to convey through auditory means. Additionally, there is increased connectivity between the visual cortex and prefrontal cortex and the attentional network when processing soundscapes through a SSD (Murphy et al., 2016). This further lends itself to the theory that it is the brain that 'sees', creating and testing sensory hypotheses, and is independent of where those signals are coming from, be it biological sensory faculties or mechanical interventions (Bach-y-Rita & Kercel, 2003).

Auditory Approaches

The vOICe is arguably the most used and cited vision-into-audio device, developed by Peter Meijer, the original version comprised of converting the image from a television camera into a grid of 4096 pixels, each pixel playing different grey tone noise (Meijer, 1992). The modern rendition of the device is an algorithm that can be used on a standard computer, or android mobile phone system (using the phone's camera as an input). As such, the resolution has increased dramatically, up to 25,344 pixels. In fact, on the high end of performance using the vOICe, some participants achieved a visual acuity of 20/200 on the Snellen tumbling E test after training with the device for up to 101 hours (Striem-Amit et al., 2012). While 100 hours of training may sound intensive and incidentally represents some of the highest reported logged training hours in SSD research, in terms of sensory perception, this constitutes only a week of wakefulness for a typical adult (Bin et al., 2012). The visual system in humans takes far longer than a week to develop and continues to develop well into childhood (Brémond-Gignac et al., 2011; Lewis & Maurer, 2005; Mayer & Dobson, 1982).

Immersive use of the vOICe over a period of years, measured by self-reported, interview-style questions, fascinatingly describe the perceptual phenomena of spatialised patterns of light, and report that the vOICe provides them with 'sight', rather than soundscapes (Ward & Meijer, 2010). Some have compared the experience offered from a SSD to a form of artificially acquired (or synthetic) synaesthesia (Proulx, 2010; Ward & Wright, 2014).

The resolution of the vOICe is much higher than many other SSDs which is made possible by scanning information from left to right (typically at 1 second intervals), providing one column of pixels at a time for interpretation, instead of sonifying the entire scene at once. The scans help to prevent information overload to the user, as receiving so much information all at once would likely sound like an uninterpretable cacophony of noise. While not receiving information all at once is a strength of the vOICe in terms of object identification, this method of sonification is perhaps less ideal for fast paced locomotion activities; in that it lacks the ability to reproduce depth information, and cannot update information quickly enough to account for the everchanging environment (for example, when crossing the street). The SoundSight is an alternative SSD that may offer some improvements over the vOICe (Hamilton-Fletcher et al., 2021b), for exercise purposes, as it utilises depth information from an iPhone's dual camera system and can provide spatial information in an 'all-at-once' fashion to quickly update to the changing environment. While the device can use other input methods, it was predominately developed to be used as a handheld SSD, and therefore, may not be completely suited to exercise that requires the hands to be available. Other vision-into-audio devices include, but are not limited to, the eyeMusic (Abboud et al., 2014), the PSVA (Capelle et al., 1998), and the Vibe (Hanneton et al., 2010).

The BrainPort

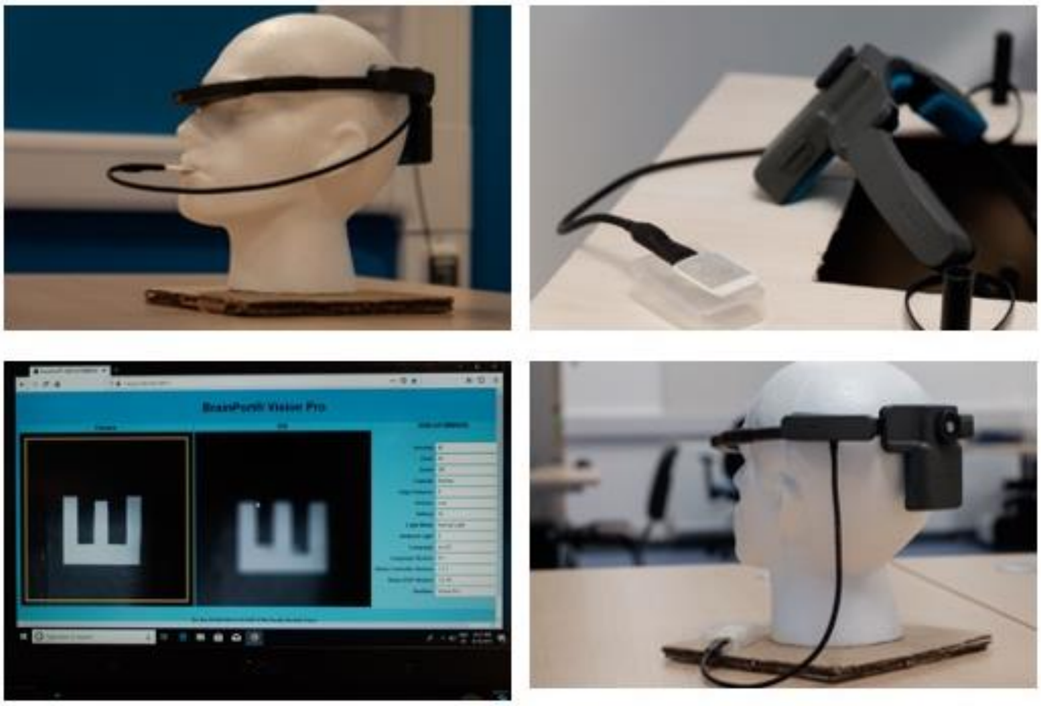
Unlike the vOICe, 'the BrainPort', is a vision-into-tactile device that offers the substituted signal in an 'all at once' fashion. The BrainPort has been through several different iterations. It originally started out as the Tongue Display Unit (TDU), a 49-pixel display (Bach-Y-Rita et al., 1998), followed quickly by a 144-pixel display (Bach-Y-Rita et al., 2003; Sampaio et al., 2001). The TDU was commercially developed by Wicab, Inc. into the BrainPort V100 (Wicab, WI, USA) which was CE approved in Europe in 2013 and FDA approved in the USA in 2015 (Stronks et al., 2016). The BrainPort V100 updated the display to 400-pixels connected to a pair of camera glasses and a small hand-held remote to control the device. The BrainPort Balance was also developed alongside the V100 for the purpose of providing electro-tactile vestibular substitution for people with vestibular loss (Bach-y-Rita et al., 2005; Danilov et al., 2007; Danilov & Tyler, 2005). In 2018, Wicab, Inc. fully updated the V100 into the BrainPort Vision Pro. The Vision Pro is a stand-alone integrated unit that does away with the glasses-mounted camera and instead uses a forehead mounted camera connected to a band that sits around the head, with a processing unit at the back (see Figure 1). Wicab, Inc. also produce the BrainPort Balance Plus, their second-generation vestibular substitution system. As the Vision Pro is the newest rendition, it is somewhat lacking in research, with most experimentation utilising the V100 (see Grant et al., 2016; Stronks et al., 2016). The few studies that have used the Vision Pro have reported promising results. After one year of device use, participants could perform tasks such as successfully navigate, avoid obstacles, and locate doors with the BrainPort (Grant et al., 2018). Participants can also identify letters and some words using the BrainPort if allowed to trace over the spatial pattern with their tongue (Grant et al., 2018; Pamir et al., 2019, 2020). However, it is worth emphasising that despite the technical possibility of 'reading with the tongue', the practicality of doing so arguably is outweighed by more effective methods such as screen readers.

The BrainPort is not without fault, its modern incarnation, the BrainPort Vision Pro, has 400 pixels, capable of producing a detailed image (see Figure 1). This is an increase in resolution from early versions of the device which could substitute 144 pixels (Kaczmarek, 2011; Sampaio et al., 2001). However, a three-fold increase in resolution has not been reflected in user-performance with the device (Grant et al., 2016, 2018); perhaps there is irrelevant data being presented to the user, and potentially distracting, or overloading, the user from useful features. Research with the Cthulhu Shield (an Arduino compatible tongue interface) shows positive results utilising only 18 pixels (Allison et al., 2020; Moritz Jr. et al., 2017), further demonstrating that high resolution SSDs are perhaps unnecessary for many tasks.

Other vision-into-tactile devices include, but are not limited to, the TVSS (Bach-y-Rita et al., 1969), the VibroVision Vest (Wacker et al., 2016), and the EyeCane (Maidenbaum, Hanassy, et al., 2014).

Figure 1

The BrainPort Vision Pro



The Tongue as an Interface for Assistive Technology

The tongue has several potential benefits for sensory substitution which have been previously championed by past work with the BrainPort (Chebat et al., 2007; Sampaio et al., 2001). Briefly, the tongue is incredibly sensitive to haptic stimulation; wet, and therefore ideal for electrotactile stimulation (a low energy method of generating haptic sensation); leaves the auditory modality available; and leaves the hands free. Such benefits may have important implications for activities such as navigation and undertaking physical exercise. Yet, while research has demonstrated the impressive physiological sensitivities of the tongue (Aktar et al., 2015a, 2015b; Lv et al., 2020; Miles et al., 2018; Okayasu et al., 2014), very little is known about tactile perception on its surface. Reviews of the tongue's somatosensory awareness tend to suggest that the reason for this is in part due to difficulties in measurement and stimulation (Haggard & de Boer, 2014; Sakamoto et al., 2010); many researchers must develop unique apparatus to test various capacities of the tongue. Historically, tactile sensations have been studied using thin nylon micro-filaments to provide localised stimulation (Henkin & Banks, 1973), however, this method is temporally limited. Here, the BrainPort provides an ideal tool to investigate the tongue further, as a commercially produced device, it can offer researchers consistency in their investigations. Further, it does not suffer with the temporal restrictions that touching nylon filaments does, opening new avenues for perceptual research; including, critical knowledge for sport and exercise, for which temporal attentional components are valuable. In this case, the BrainPort is both the tool to study, and the tool of study.

Tongue interfaces are not limited to the BrainPort. Development has occurred in tongue interfaces for wheelchair control (Kim et al., 2013; Lontis et al., 2014, 2016), and computer control (Huo et al., 2008; Huo & Ghovanloo, 2010; Struijk et al., 2009). These devices utilise inductive electromagnetic sensors, rather than electrodes, and so are restricted to user input only and cannot be used as a non-visual display. The Cthulhu Shield (Sapien LLC, CO, USA) is somewhat more similar to the BrainPort, employing electrodes that directly stimulate the tongue's surface. The Cthulhu Shield's display only contains 18 electrodes, meaning it cannot display complex images, but makes up for this deficit by allowing input in addition to output; the device can act as both a display and input device. The Cthulhu Shield is an Arduino-based device that requires programming and is not marketed as a vision-assistive technology, instead it focuses on making electrotactile tongue interfacing more accessible. Another example of an electrotactile tongue interface, that is similar to the Cthulhu Shield, is the Tongueduino (Dublon & Paradiso, 2012), also an Arduino-based device, using a grid of 9 electrodes to stimulate the tongue with localised information. Other methods of interfacing with the tongue include electromyography (Sasaki et al., 2016), camera-based gesture (Niu et al., 2019), and pressure switches (Cheng et al., 2014). Although, like the previously mentioned inductive sensor-based devices, these examples cannot output information to the tongue, rather, they are solely used as means of inputting information for computer interaction. In terms of displaying information to the tongue, electrotactile is likely the best form of feedback available. This is due to the morphology of mechanoreceptors on the tongue's surface. Notably, Merkel cells (slow adapting type I fibres), Ruffini endings (slow adapting type II fibres), and Meissner corpuscles (rapid adapting type I fibres) all contribute to a plethora of possible highly sensitive sensations on the tongue's surface (Trulsson & Essick, 2010). Slow adapting fibres persistently respond to static mechanical stimuli, while fast adapting fibres respond only to initial onset of a stimulus (see Haggard & de Boer, 2014, for review). The morphology of these fibres across the surface of the tongue means that the most vivid type of tactile sensation would likely be light touch continuous vibration (Haggard & de Boer, 2014), which consequently, is the type of stimulation provided by electrotactile tongue interfaces (Bach-Y-Rita et al., 1998; Kaczmarek, 2011). The distribution of these fibres is not uniform, with the anterior section (the tip of the tongue) possessing a greater sensitivity to tactile stimulation than the posterior section (Trulsson & Essick, 1997). Specifically, concerning electrotactile discrimination ability, the back of the tongue seems to be an informational 'bottleneck' to tactile pattern recognition (Pamir et al., 2020), with a lower spatial resolution than the tip of the tongue.

Outside of vision, the modality with the highest bandwidth for information processing is auditory (Haigh et al., 2013; Richardson et al., 2019). So why choose the BrainPort as the object of study, over an auditory device? Firstly, the substituted information takes up some of the processing bandwidth in the target modality, so by translating visual information into sound, the SSD user may have reduced capacity to use natural hearing (Kärcher et al., 2012), and this is likely emphasised in sport and exercise contexts. Secondly, the BrainPort leaves the hands free and is head mounted to allow for easier environmental interaction. Thirdly, the BrainPort has been successfully used by Erik Weihenmayer, a completely blind adventure sport athlete who has conquered Mount Everest, scaled the Nose of El Capitan in Yosemite, and kayaked the length of the Grand Canyon, to name a few of his endeavours. Despite existing articles and videos of Weihenmayer using the BrainPort successfully in a climbing gym to navigate the rock climbing routes (Levy, 2008; Twilley, 2017), no rigorous research has been done to better understand whether the BrainPort and the tongue can be used effectively by visually impaired persons to exercise.

Purpose of the PhD Project

The BrainPort has been used as a vision-aid for sport and exercise, as demonstrated by Erik Weihenmayer. However, the BrainPort has not been widely adopted for this (or any) purpose. Weihenmayer shows that the tongue might offer an ideal receptor to translate information to aid in exercise, however little is known about the tactile capacities of the tongue. Is Weihenmayer simply exceptional and his use of the BrainPort unobtainable for most? To effectively understand the feasibility of using the BrainPort, or other tongue interfaces, for the purpose of exercise, it is crucial to gain a greater understanding of how spatial information is processed on the surface of the tongue. In their review on designing SSDs, Kristjánsson et al. (2016) comment that there is a need for researchers to turn attention on understanding basic perceptual processes with SSDs and suggest that psychophysical experimentation may be a good initial avenue for gaining understanding of these processes. Furthermore, there are two primary factors that must be regarded: first, the need to evaluate the minimum perceptual information required for a given task, and second, to discern the limits of the perceptual channel to which the substituted information is to be provided to (Loomis et al., 2012). In the case of using a tongue interface as an exercise assistive device, gaining a greater understanding of the barriers to exercise participation will help to discern what perceptual information may be useful (e.g., what aspects of exercise are inaccessible and can this be lessened with additional spatial information?). The tongue is comparatively understudied in relation to other parts of the body and the other sensory modalities and so its spatial processing ability is relatively unknown (Haggard & de Boer, 2014; Sakamoto et al., 2010). To understand the limits of the perceptual channel, classical psychophysical methods can therefore be applied to the tongue to begin generating a body of knowledge about its spatial processing. This in turn, could inform future SSD developers about the information that can be successfully conveyed to the tongue, and which ‘non-useful’ information can be removed.

This PhD project first aimed to apply psychophysical methods to the surface of the tongue to establish how spatial information is interpreted on the tongue, given the spatial transformation that the brain must perform to perceive visual information through tactile representation on its surface. This study is described in Chapter 1. Then another important function to examine is how tactile attention is processed via the tongue; past works with the BrainPort have predominately focused on acuity measures with ample exploration time (e.g., Nau et al., 2013; Pamir et al., 2019; Stronks et al., 2016), however, exercise contexts require rapid orientation of attention in response to environmental change. Using the classical psychophysical method of a cueing paradigm, we examined the orientation of tactile attention on the tongue. This involved two experiments, one to explore the unimodal properties of attention on the tongue (i.e. Can humans orientate their tactile attention on the surface of the tongue?), and another to explore the crossmodal influence of the auditory modality on the tongue (i.e. Can humans orientate their tactile attention on the surface of the tongue in response to crossmodal cues?), as exercise contexts are multimodal and provide a variety of sensory feedback. These two experiments are described in Chapter 2. Chapter 3 addressed the barriers to exercise participation. Initially, this experiment aimed to assess current barriers to exercise participation for people with visual impairments and identify potential areas for technological intervention. However, due to the Coronavirus-19 pandemic, the nature of the experiment was adapted to reflect the developing situation at the time. For more details of this, please refer to the Introduction to Chapter 3 section. The General Discussion section contains a discussion of the empirical findings presented in Chapters 1, 2, and 3, and then leads on to Chapter 4, which applies the findings of this PhD thesis and proposes the concept for new tongue interface software for exercise. Specifically, to aid navigation for rock climbers with visual impairments. As this thesis is in the 'alternative format', with each chapter presented as a journal paper, the Introduction to Chapter sections provide wider context and link the narrative between studies, where context is not already provided (e.g., by the Introduction or Discussion). Finally, the Closing Summary provides a short conclusion on how the work presented in this PhD thesis adds to the literature and how this new knowledge informs the development of effective assistive technology for people with visual impairments who want to engage in sport and exercise.

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Signed	[redacted]	**Date**	02/12/2021

Chapter 1: Reading with the Tongue: Individual Differences Affect the Perception of Ambiguous Stimuli with the BrainPort

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Abstract

There is an increasing interest in non-visual interfaces for HCI to take advantage of the information processing capability of the other sensory modalities. The BrainPort is a vision-to-tactile sensory substitution device that conveys information through electro-stimulation on the tongue. As the tongue is a horizontal surface, it makes for an interesting platform to study the brain's representation of space. But which way is up on the tongue? We provided participants with perceptually ambiguous stimuli and measured how often different perspectives were adopted; furthermore, whether camera orientation and gender had an effect. Additionally, we examined whether personality (trait extraversion and openness) could predict the perspective taken. We found that self-centred perspectives were predominantly adopted, and that trait openness may predict perspective. This research demonstrates how individual differences can affect the usability of sensory substitution devices and highlights the need for flexible and customisable interfaces.

Keywords: sensory substitution; tactile interfaces; individual differences in computing; user preferences

Introduction

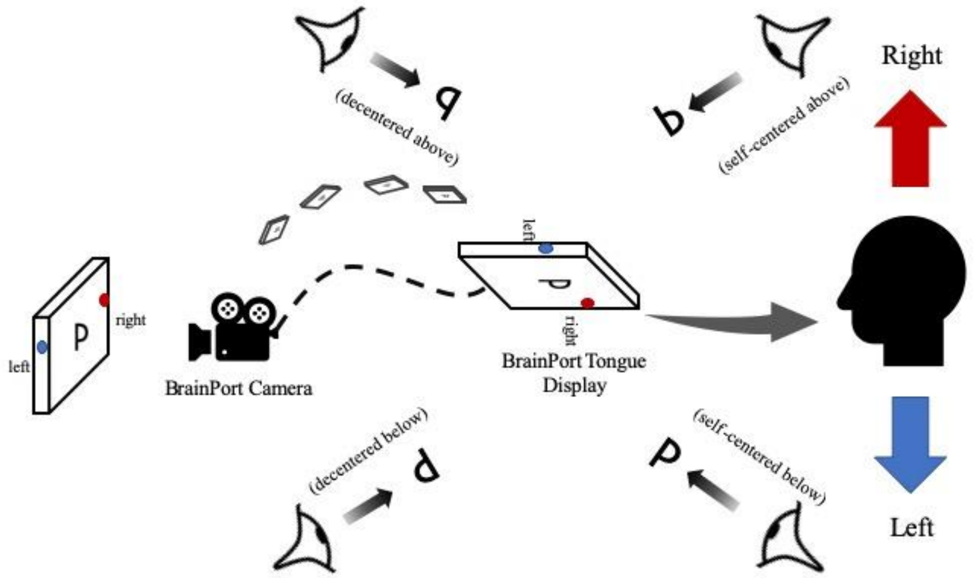
Human-computer interaction (HCI) includes a great number of interface methods, ranging from the conventional monitor, keyboard and mouse; the now widespread touch screen; and the increasingly popular voice interfaces of Siri and Alexa (Hoy, 2018). The 'BrainPort' is a device that lies towards the obscure end of the interface spectrum, providing tactile feedback to the user through electrical stimulation on the tongue (Bach-y-Rita & Kercel, 2003; Danilov & Tyler, 2005). It was developed as a vision-into-tactile sensory substitution device (SSD), a machine that converts the information available in one sensory modality into another (Stronks et al., 2016). However, it also has untapped potential for use as a novel way to provide information through tactile means that could be generalised to other parts of the body. This, in turn, can help further reveal the brain's representation of, and interaction with, space (Abboud et al., 2014; Amedi et al., 2007).

Previous research has suggested that the tongue is an 'ideal' surface for sensory displays, often citing reasons such as sensitivity, moistness (therefore a better conductor of electrical stimulation, requiring less power consumption than other tactile methods such as vibrating motors), and leaving the hands, ears, and any residual vision free for other purposes (Bach-y-rita, 2004; Chebat et al., 2007; Sampaio et al., 2001; Van Boven & Johnson, 1994). Using the tongue as a display surface provides some unique issues that must be considered. As the camera is designed to be head-mounted, the video feed is as one would view on a traditional screen (see Figure 1 for how the BrainPort converts a visual signal). However, because the tongue is a horizontal surface, the video feed must undergo some transformation. As there are not many situations that can quickly be brought to mind in which humans naturally convert vertical space into horizontal, the need for a device to be intuitively mapped may be consequential to enjoyment and uptake, or dropout from device learning (Birk & Mandryk, 2013). Furthermore, individual differences such as being introverted and extroverted may affect how a user converts this information (e.g., introverted users may take a more self-centred perspective than extroverted users when transferring the vertical information to horizontal). In fact, personal factors like gender (Tarampi et al., 2016), and personality (Shelton et al., 2012), can influence how the brain relates to space.

The sensations provided by the BrainPort are novel, and consequently, their processing is cognitively complex. Previous work has shown the benefits of dedicated practice to improve SSD comprehension and also BrainPort specific comprehension (Stronks et al., 2016). However, as there are a number of ways in which the picture from the BrainPort could be flipped to the flat surface of the tongue, we investigated the influence of camera orientation, gender and personality on the perception of directionally ambiguous stimuli; this will provide insight about the impact of seemingly fundamental individual differences in the brain's integration of space.

Figure 1

Possible interpretations of the ambiguous letter 'p' when viewed through the BrainPort's tongue display.



Note. The top of the camera's field of view appears on the back of the tongue. Whichever perspective the user adopts, will change the percept of the stimuli.

To better understand the process of transforming vertical spatial information into the plane of a horizontal tongue display, and how the BrainPort achieves this, it might be helpful to draw the letter 'p' on a note of paper (mentally or physically). Then, flip the paper over and trace over the 'p' on the opposite side to create a single shape through the plane of the paper (i.e., if the reader were to cut around the shape, it would be the same on either side). To imagine how the BrainPort converts an image, hold the note in front with both hands, like an open book (the note should read 'p'). Now, bending the elbows, bring the top of the 'p' toward the mouth until the paper is horizontal (looking down at the note should read ‘b’), this is the shape that would be electro-tactilely vibrated into the tongue (as if one were to drop the paper ‘p’ onto the tongue).

The fields of sensory substitution and augmentation have several widespread applications which all would benefit more in-depth literature from which to draw on. The most discussed application for this technology is arguably, to recover some perceptual losses from a sensory impairment, with many individuals already using SSDs in their everyday life (Ward & Meijer, 2010). There are also specialist uses being considered where further knowledge about how the brain interprets the SSD are unquestionably vital. One example of this is tactile feedback for firefighters; when smoke levels are too high for clear visual search, an ultrasonic rangefinder paired to haptic gloves can offer a new search perspective (Carton & Dunne, 2013). Another important employment of tactile feedback research is being used in Human-Drone interfaces (Abdullah et al., 2017; Funk, 2018). As drones become more available and capable of more complex tasks, providing environmental or navigational information through tactile means could allow the pilot to concentrate visual attention on flying.

As the display needs to map to the external world and we cannot assume that a display of information to any given sense or (in the case of tactile feedback) any location on the body, would be the same as others, so introducing the TDU for non-blind, non-vestibular, other HCI uses, requires this knowledge produced here (e.g. which way is ‘up’ on the tongue?). While camera orientation is not a unique consideration to tongue displays, we posit that the uniqueness of translating information from an external vertical plane to an internal horizontal one is, so we assessed that here as well.

Related Work

Brown, Macpherson, and Ward (Brown et al., 2011a) conducted an experiment with the vOICe, a vision-to-sound SSD, where they examined the effect of different camera conditions on ease of object location and discrimination. They found that holding the camera with the hand, led to more easily identified objects compared to head mounting, possibly suggesting that individuals can readily shift their perspective to that of the camera. This could potentially mean that when identifying objects through an SSD hand-held camera, users take a camera-embodied perspective (and move their locus of attention with the camera lens). Brown (Brown et al., 2011a) chose to examine the difference between hand-held and head-mounted camera angles, rather than between different positions for the hand-held camera or head-mounted camera. This left a gap for future research to examine the usability of different hand-held camera orientations (for example, in front, or above).

Recent research into low-resolution SSDs (only 128 pixels) found that participants could still make remarkably accurate spatial judgments (Richardson et al., 2019). While low-resolution devices are useful for gross tasks, such as movement and navigation, they may not provide enough information to form complex perceptions. Studies using the BrainPort have previously demonstrated that participants can quite easily identify rotating letters, reducing in size down to only a few millimeters on the tongue (Chebat et al., 2007; Nau et al., 2013; Sampaio et al., 2001). These experiments typically used the Snellen Tumbling E test (a rotating E that gradually decreases in size), which is useful to measure acuity, as by an optician, but not perspective on a tongue display, as the E is symmetrical along the horizontal axis. As such, the E would appear the same when viewed from above and below. To date, no one has yet tested the BrainPort with truly ambiguous letters that would change meaning when viewed from alternate perspectives, including a combination of decentred, self-centred, above, and below.

A study from Arnold, Spence, and Auvray (Arnold et al., 2016) used vibrotactile motors to stimulate the letters of b, p, q, and d on the torso of participants to observe which perspective was taken. They reported that three different perspectives could likely be taken: 1) head-centred (as if one was looking from the head down at the letter), 2) trunk-centred (perceiving directly forward from the torso), and 3) decentred (perceiving as if looking at the torso from a second-person perspective), which were adopted by 30%, 50%, and 20%, of participants, respectively. Work previous to that of Arnold and colleagues used similar methods to examine adopted perspectives (Ferrè et al., 2014; Parsons & Shimojo, 1987; Sekiyama, 1991), however, in Arnold and colleagues' study a tactile matrix was used rather than having an experimenter draw the letters onto participants. Removing the experimenter seemed to decrease the likelihood of adopting a decentred perspective in comparison to these past works, although not completely. Arnold, Spence, and Auvray (Arnold et al., 2016) suggest that to some individuals, the decentred perspective 'may be their default' (p. 31), but for most, the presence of an experimenter creating the symbols, sways the perspective to that of the experimenter (decentred). In addition, a study found that individuals with good social skills can more freely adopt a decentred perspective (Shelton et al., 2012); by taking the other's perspective spatially, they can further grasp the other's perspective empathetically (Schober, 1993). High trait extraversion and openness, and gender may also serve as markers for the flexible social skills that are required to step into the others' perspective [16, 23]. For example, females have been shown to perform more successfully than males on activities designed to test spatial perspective taking, when the task is dependent on social factors (Tarampi et al., 2016).

A follow up review conducted by Arnold, Spence, and Auvray (Arnold et al., 2017) indicated that spatial, personal, and interpersonal factors could influence the perspective adopted when perceiving tactile letters on the body; as part of this review, they included a meta-analysis of studies presenting tactile letters to the head (on the forehead). When discussing the possible perspectives that could be adopted in response to a tactile letter on the forehead, the most common distinctions were found between decentred (looking directly at the forehead from a second-person perspective), or self-centred (perceiving directly forward from the forehead). Furthermore, Arnold et al. (2017) showed that most studies reported the self-centred perspective as most often adopted. However, these experiments do not consider that a perspective could be taken from the eyes, looking up at the letter, much in the way that some participants took a head-centred perspective in the torso experiments (looking down at the letter). The current rhetoric seemingly classifies that head-centric perspectives are generally adopted because it is the head in which vision resides (Arnold et al., 2017; Bertossa et al., 2008), but this may depend on where the stimulus is located (e.g., the head rather than the torso).

We aimed to test some of the spatial and personal factors that could contribute to what perspective is taken when using the BrainPort. To examine spatial factors, we drew upon the work of Brown et al. (2011) and hypothesised that camera position would affect the perspective taken, as they found that holding a camera allowed for more successful object identification, possibly due to adopting the camera's point of view (PoV). We next examined the effect of certain personal factors (extroversion and openness) on decentred perspective. These factors were chosen as past research suggests that they may indicate social skills, and an ability to relate to others, spatially and empathetically (Eysenck, 1961; McCrae, 1996; Shelton et al., 2012).

Methods

Participants

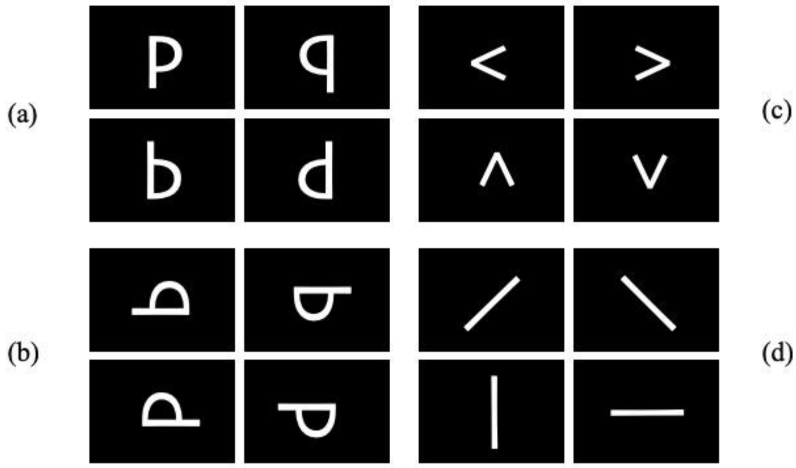
Thirty-six individuals volunteered for the experiment (18 female, mean age = 20 ± 1 years), and were reimbursed £5 for their time. All the participants gave written informed consent but were unaware of the study's purpose. Ethics permission was granted by the Department of Psychology Research ethics committee, University of Bath [reference no. 0125-18-14]. After each participant's data collection was completed, they were debriefed, revealing all aspects of the study. The participants all reported no sensory impairments, and the majority were righthanded (N = 32). Sighted individuals were chosen (rather than visually impaired) as the specifics of the present experiment hoped to convey individual variation with anyone using a tongue display, rather than information pertaining to blindness or visually impairments only.

Materials and Measures

In addition to the ambiguous letters, for greater generalisability, further stimuli were used in the present study giving four distinct stimulus groupings: 1) four letters; 2) two ambiguous letters 'd' and 'q' rotated by 90° in either direction; 3) arrowheads; and 4) lines of ascending, descending, vertical, and horizontal orientations (see Figure 2). The rotated letters served as a functional control since the participants would not be able to interpret the letter (see Figure 2b). The ambiguous letters (Figure 2a) could be interpreted in one of four ways depending on perspective, in that the letter 'p' could appear to be either a 'p', 'b', 'q', or 'd' from varying positions. However, the arrowhead (Figure 2c) and diagonal line (Figure 2d) stimuli could only realistically differ in perspective between opposite pairings (left vs. right, up vs. down, ascending vs. descending). The lines were included as additional measures of accuracy, but not of perspective-taking, as their appearance remains stable independent of perspective in the case of the horizontal and vertical orientation. That is, the diagonal lines could be interpreted as ascending or descending depending on whether they were viewed from above or below, from either the decentred or self-centred perspective, hence no measure of perspective is possible with these stimuli.

Figure 2

The stimuli that were presented to the BrainPort camera, the letters (a), rotated letters (b), arrowheads (c), and lines (d).



The BrainPort V100 (Wicab, WI, USA) was used for the experiment. This is an older version of the device, which has since been updated into the form of the BrainPort Vision Pro. The device consists of a headset and a controller. The headset is formed of a camera mounted to sunglasses, and the tongue display (an array of 400 electrodes, arranged 20 × 20, spaced at 1.32 mm apart); the total size of the tongue display (29.5 mm × 33.8 mm × 7 mm) allows it to sit on the tongue comfortably and inside the mouth (Grant et al., 2016). The controller houses the lithium-polymer battery pack, that provides the BrainPort with up to 2 hours of use, and also handles the image processing, along with buttons to control the output (for example, zoom, intensity, contrast). The vRemote (also developed by Wicab, WI, USA) software allows a laptop to wirelessly view the configured settings, the camera input, and the tongue display output. Figure 3 shows how the BrainPort renders the video image to the tongue display, as viewed through the vRemote program. The initial settings were standardised (intensity = 50; zoom = 17°; invert = off; contrast = high); however, the intensity setting was manipulated to provide optimum comfort for the participants, while maintaining a clear projection of the stimulus, based on individual preferences.

Procedure

Prior to conducting the main BrainPort experiment, participants completed the Big Five Inventory (BFI-44; a questionnaire-based measure that aims to assume individuals' personality traits, succinctly; (John et al., 1991). The participants' background information (age, gender, dominant hand) was collected, and they were blindfolded before being guided into the experimental room (to prevent visual information from influencing the user's performance), then sat in front of the BrainPort. Before any data collection commenced, each participant was encouraged to explore the tongue display to familiarise themselves with it, while the experimenter adjusted the intensity to achieve the participant's optimal comfort. A short training protocol was used to give the participants some practice with the stimuli and to make sure they understood the task. The training consisted of five trials, identifying a given number of dots, and explaining their appearance (e.g., two dots on the horizontal axis). In this phase, the researcher would give verbal feedback once a response had been made as to whether it was correct or not.

The main task consisted of three different conditions, each with 18 trials (two of the trials presented in the data collection were for other experiments, 16 of the trials were analysed for the present experiment, with one trial per stimulus, see Figure 2). Participants were allowed up to 10 seconds to respond to each stimulus with a verbal answer. Participants were informed of the stimulus group and, therefore, knew whether to respond with a letter, arrow direction, or line orientation depending on the trial. The conditions consisted of no camera (NoCAM), vertical camera (VertCAM), and horizontal camera (HozCAM). In the no camera condition, participants were told that the stimuli were pre-recorded. In the vertical and horizontal conditions, the participants were given a fake camera to hold in a vertical and horizontal position (see Figure 4), respectively.

Figure 3

A screenshot of the BrainPort's input camera signal, and its rendered tactile output on the tongue display.

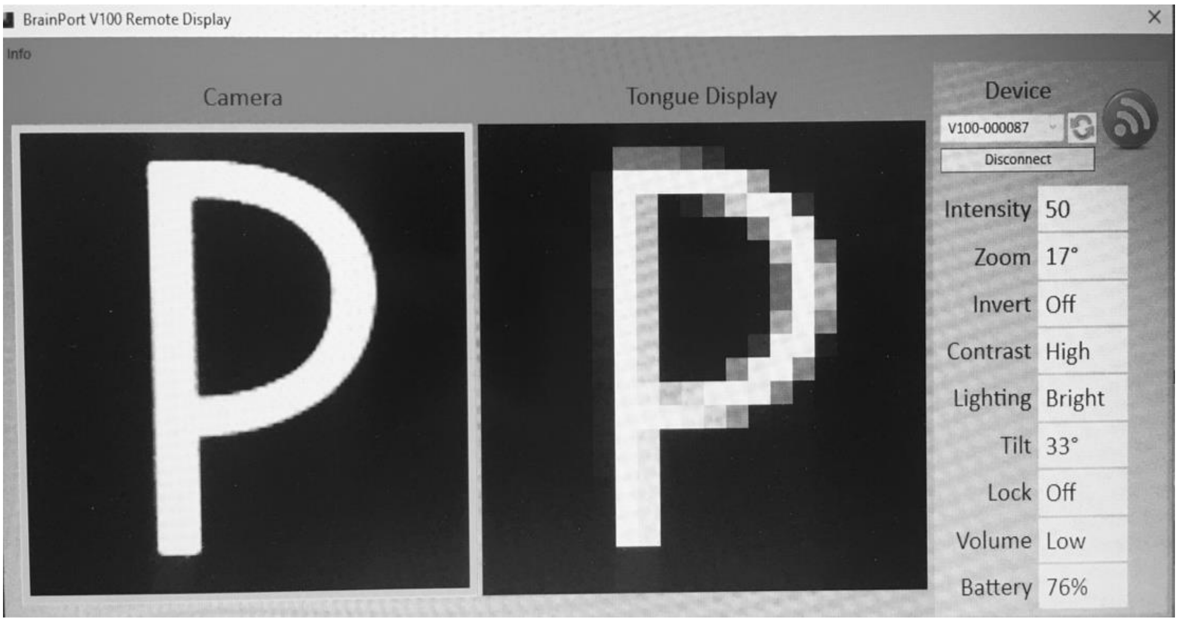
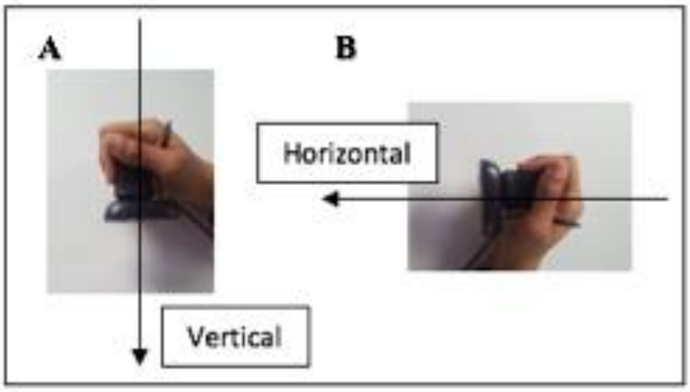


Figure 4

A demonstration of camera position in the vertical (A) and horizontal (B) camera conditions.



The researchers would occasionally make comments about steadying the camera to perpetuate the deception. The reason for using a fake camera was to facilitate identification of the stimuli and to allow for valid comparison to the no camera condition. The stimuli were identical in every condition and presented in a random order. Participants were given a break between conditions; in total, the experiment took roughly one hour to complete.

Data Analysis

Due to the different number of possible interpretations depending on stimuli type, the letter-based stimuli were coded slightly differently to the arrows and lines. Additionally, the vertical and horizontal lines were not factored into perspective-taking, only for calculating response accuracy.

For the letters, responses were coded with a number from 1 to 4 depending on the given answer (for the letter ‘p’: 1 = ‘b’ = self-centred from above; 2 = ‘p’ = self-centred from below; 3 = ‘q’ = decentred from above; 4 = ‘d’ = decentred from below, refer again to Figure 1). For the arrowheads, responses were coded as only either self-centred or decentred, as the direction would not change from higher or lower perspectives (for the arrow ‘<’: 1 = ‘left’ = self-centred; 4 = ‘right’ = decentred). Coding responses in this manner was arbitrary and aimed to force a clearer separation between self-centred and decentred during the analysis. The letters could be used to tease apart ‘decentred’ and ‘self-centred’, including the further perspectives of ‘above’ and below’. This was done by examining the most frequently adopted perspective, so that if a participant responded to the letters with perspectives ‘1, 1, 3, 2 (or self-centred above, self-centred above, decentred above, self-centred below’, they would be considered as predominantly self-centred above. We used a frequency driven perspective classification, as explained in the previous example, rather than using the average, as calculating the average across the four participant’s responses would have returned imprecise results. That is, taking the example above the average of 1, 1, 3, 2 responses would have been around 2, suggesting that that participant had a self-centred below perspective, despite only responding with perspective 2 on one occasion. If a participant reported different perspectives an equal amount of time, for example ‘2, 2, 3, 3’, or ‘2, 1, 4, 3’, then that participant was considered as having a mixed perspective. Accuracy for all stimuli was also measured by recording whether the answer was correct or not according to the BrainPort (e.g., if a ‘P’ was shown to the BrainPort camera, and the response ‘P’ was given), and is reported as a proportion across all trials, split between the camera conditions.

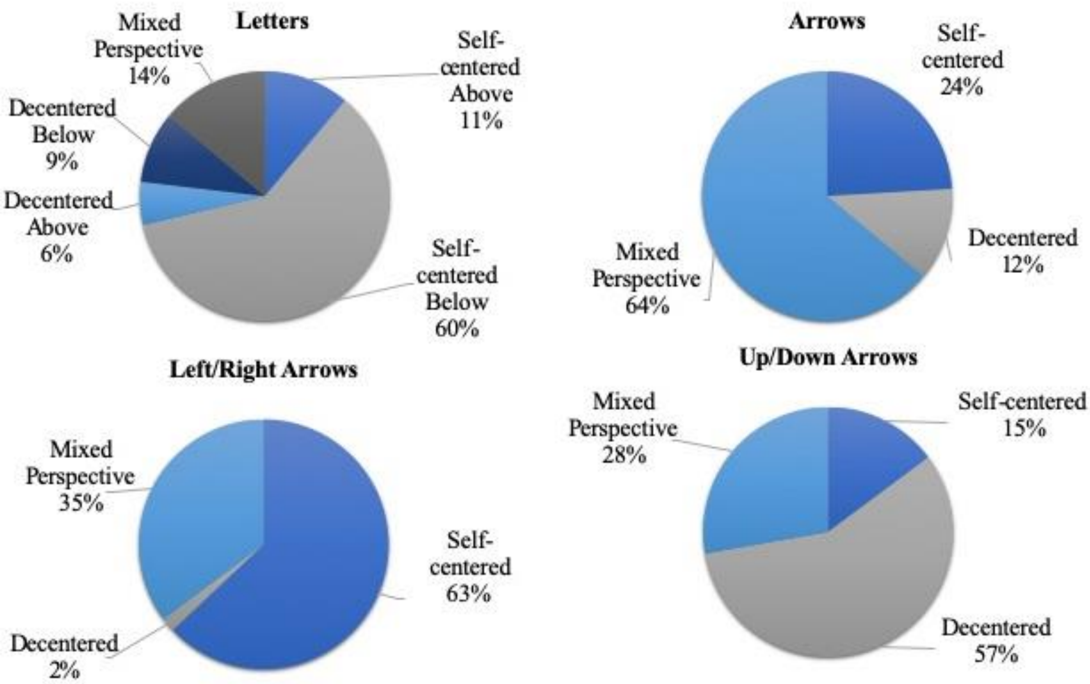
Results

As the data were predominately categorical (with the exception of: proportion of correct responses, and extraversion and openness personality questionnaire scores), a chi-square test revealed that there was no association between camera orientation and perspective taken for the letters ($X^2(8, N = 108) = 10.04$, $p = .262$) or arrows ($X^2(4, N = 108) = 4.39$, $p = .356$). There was also no association between gender and perspective adopted for letters or arrows ($X^2(4, N = 108) = 3.19$, $p = .538$; ($X^2(2, N = 108) = 4.29$, $p = .117$, respectively).

Figure 5 shows the percentages of adopted perspectives for the letters and arrowheads within the participants and, it also shows the variation within the arrowhead stimuli between left/right and up/down arrows. As described above, participants were described as having a 'mixed perspective' in the case that they had equal self-centred and decentred responses, or no clear mode of response (e.g. for the letters, answering with each of the possible perspectives).

Figure 5

The pie charts at the top display the percentages for each adopted perspective when participants observed the letters and arrows with the BrainPort. The pie charts at the bottom display the different percentages adopted for the arrowhead stimuli.



Next, we examined the level of accuracy for the different types of stimuli (proportion of correct responses according to the BrainPort; e.g. if a 'p' is shown to the camera, participant responded with a 'p'). Median proportions can be found in Table 1. Wilcoxon

Signed Rank tests (with a Bonferroni correction, giving an accepted *P* value of .008) showed that the accuracy in interpreting the letters was significantly higher than that of rotated letters ($Z = 6.28$, $p < .001$); letters less than arrows ($Z = 3.09$, $p = .002$); letters less than lines ($Z = 6.91$, $p < .001$); arrows more than rotated letters ($Z = 7.51$, $p < .001$); arrows less than lines ($Z = 5.61$, $p < .001$); and, lines more than rotated letters ($Z = 8.91$, $p < .001$). Also within the arrowhead category the left/right arrows were correctly identified significantly more than up/down arrows (75% and 66%, respectively) across all trials ($Z = 2.34$, $p = .02$).

Table 1

Medians and interquartile range for proportion of correct answers given to the different stimuli when observing them through the BrainPort (e.g. if a 'P' is shown to the camera, the participant responds with 'P').

Camera Condition	**Total Correct**		**Letters**		**Rotated Letters**		**Arrows**		**Lines**	
	Median	*IQR*	*Median*	*IQR*	*Median*	*IQR*	*Median*	*IQR*	*Median*	*IQR*
No Camera	.75	.27	.75	.75	.25	.25	.75	.50	1	.25
Vertical Camera	.75	.50	.50	.75	.25	.50	.75	.50	1	.25
Horizontal Camera	.79	.32	.75	.75	.25	.25	.75	.50	1	.50

The level of extroversion and openness were used as predictors in a multiple linear regression analysis to examine the effect of these personality traits on participants' proportion of correct responses (according to the BrainPort), which serves as a proxy for perspective taking (if a person were to answer correctly 100% of the time, they would likely be defaulting to a self-centred perspective). Proportion of correct answers was chosen to be the criterion as it is measured as continuous, rather than categorical, such as adopted perspective. We predicted that extroverted and open individuals would be more likely to adopt a decentred position and would therefore offer more incorrect answers. Collinearity was tested on the predictors, and openness and extraversion proved to be within accepted values (tolerance = .96, VIF = 1.04; tolerance = .96, VIF = 1.04 respectively). Visual examination of a P-P plot and a scatterplot of the standardised vs. predicted residuals showed no cause for concern. Additionally, autocorrelation was deemed at an acceptable level (Durbin-Watson =1.83). The results of the multiple regression analysis showed no effect of the combination of openness and extraversion on perspective-taking, $F(2,40) = 2.74$, $p = .077$, with an R^2 of .13 and an $R^2_{Adjusted} = .08$. However, examining the predictors individually showed that extroversion did not predict perspective-taking, but openness may do ($ß = -.36$, $t(40) = -2.32$, $p = .026$).

Discussion

The presented study aimed to identify the dominantly adopted perspective when using the tongue via the BrainPort to interpret ambiguous stimuli. Additionally, it sought to examine whether camera orientation (a spatial factor), trait extroversion, and openness (personal factors) had any effect on the adopted perspective. The results indicate that self-centred was the most adopted perspective, and that camera orientation did not have any effect on the adopted perspective. Specifically, for the letter stimuli, slightly more than half the participants (60%) generally took a self-centred from below perspective, as if one were looking up at the tactile letter on tongue, from inside their mouth; and just over a tenth (11%) took a self-centred from above perspective, as if looking down at the tactile letter on the tongue from their eyes. Openness (but not extraversion) may slightly predict the adoption of a decentred perspective. Although, the multiple regression equation was marginally non-significant when factoring in both openness and extraversion.

The results do align reasonably well with Arnold et al. (2016), in that the majority of individuals adopt a self-centred perspective when perceiving the ambiguous letters. However, in later work by the same authors, they commented on the potential for perspective-taking to be predominated by a vision-centric point of view when perceiving tactile stimuli (Arnold et al., 2017). This does not appear to be the case with the BrainPort, with 60% of participants taking a view from below, as if from inside the body, rather than from the eyes per se.

The observed effect of openness on likeliness to adopt a decentred perspective aligns reasonably well with the work of Shelton and colleagues (Shelton et al., 2012), as they found those with good social skills, more freely adopt a decentred perspective. However, finding that gender did not offer a tangible association with perspective-taking is somewhat surprising. While both males and females can be considered to predominantly adopt a self-centred perspective, the females did so more consistently. One study examining the gender effect on perspective-taking found that females perform better at spatial tasks with a social component (Tarampi et al., 2016). While our task did not include a social component, we expected females to adopt a decentred perspective more readily as a reflection of their social relatability. Future replications of this research with tongue displays may wish to try running the experiment both blindfolded (as presented here), and unblindfolded with the addition of a social agent. It may be that females predominantly change their perspective only in the apparent presence of another. It was also surprising to find that camera orientation did not exhibit an association with perspective. The results of Brown et al. (2011) showed that the camera position on SSDs could have a dramatic sway over task performance. One possibility for our result is that using a fake camera (to control image presentation for each participant) did not offer the same proprioceptive feedback that an actual camera would.

As the BrainPort does not allow for a secondary camera to be connected (being designed as a standalone unit), it was not feasible to use a live camera in the present study. Perhaps in the future, a programmed accelerometer could be connected to the fake camera to wobble the stimuli on a screen, to emulate an actual handheld camera more effectively. The lack of 'hackability' in the BrainPort is surely a limitation set by the device for generalisability in research settings but does not limit the knowledge generated about tongue displays (i.e., research with the BrainPort is useful for furthering tongue display development, despite customisation issues). One possible way to overcome this could be found in the 'Tongueduino', a fully programmable, lower resolution tongue interface (Dublon & Paradiso, 2012), that offers a lower cost alternative to the BrainPort. Although, in the present case, the Tongueduino's resolution would be incapable for presenting complex shapes, such as letters; hopefully, further BrainPort research can improve the functionality of lower cost and hackable tongue displays.

In previous work, there have been results that suggest that sighted people more naturally tend toward a head-centred perspective. The unique interface of the tongue display allows us to tease apart 'head-centred'; indeed, the BrainPort allows for two head-centred perspectives (from the eyes down, and the tongue up). Arnold and colleagues (2017) suggest that one possible reason for this is that sighted individuals have a high reliance on vision, due to the wide bandwidth of information conveyance, and therefore other types of perception also gravitate toward the eyes. They also found that when participants were forced to adopt a different perspective, their tactile perception accuracy significantly reduced. Our findings suggest that this link may exist, but in a fine form; the majority of our participants took a tongue-centred perspective (which is incredibly novel without prior BrainPort experience) and responded with generally high accuracy toward stimuli (around 75% correct responses). Arguably we cannot conclusively remark whether the BrainPort forces unnatural perspectives, as camera orientation did not display any effect on perspective adoption, but grounds for speculation surely exist. Additionally, as the experiment was short (to measure intuition rather than learning), there was little chance of brain plasticity changes, to adapt to the specific interpretation of the BrainPort; there could be a scenario where all the perspectives were ‘unnatural’.

One of the more intriguing findings is the difference in perspective between the left/right arrows and the up/down arrows. For the left/right arrows, the majority of participants (63%) took a self-centred perspective and on average were more often correctly identified than in the up/down arrow trials (75% compared to 66%). There was also a reverse to the majority adopting a decentred position in the up/down arrows (57%). This potentially could support the idea, that forcing unnatural perspectives reduces the accuracy of stimulus interpretation, as suggested by Arnold and colleagues (2017). The BrainPort could unnaturally flip up and down arrows in terms of perspective taken, while left and right arrows remain the same when translated onto the tongue (left still points left, but up points to behind the person).

The fact the perspective-taking is not uniform, even within a group that was given a small amount of training, combined with evidence from Arnold et al. (2016; 2017), that adopting an unnatural perspective detracts from tactile symbol recognition, would strongly suggest that making SSDs as customisable as possible, would be advantageous. Additionally, Wicab, the company that designs and builds BrainPorts, state on their website that training is required for the BrainPort, which is undertaken at dedicated training centres. We propose to Wicab that prior to their training program, they collect perspective-taking data from the user, and use that to calculate which orientation is naturally preferred; setting up the device in this way may decrease learning time. The ambiguous letters are ideal for such an exercise; revealing the dominant natural perspective and calibrating the BrainPort to match.

It was somewhat surprising that such a high percentage of participants favoured the 'self-centred from below' perspective. While the BrainPort training was short, it is perhaps likely that the participants quickly learned the orientation to which the BrainPort flipped images. This is supported by the high percentage of correct answers, independent of perspective adoption (demonstrated by the arrowheads: left/right stimuli were correctly answered 75% of the time and were predominantly self-centred; up/down were correctly answered on 66% of trials, but the majority of responses were decentred). This would suggest that the demonstrated differences in perspective-taking are conservative and that with no training, a more considerable variation should be expected. However, for research purposes, basic training is challenging to remove from a protocol; without any training, responses would likely be too inaccurate to draw any conclusions from the data. Training people with visual impairments who intend to use the device in daily life would not suffer this issue. Additionally, while the present paper examined the specifics of perspective taking, there are many other avenues that should be explored to help inform potential BrainPort daily users, including, hygiene, acceptance, and wearability.

Impact

The impact of the presented study has the potential to dramatically improve the time it takes to gain familiarity with novel displays (like the BrainPort). If interface designers consider from the first stage, the possible individual differences between users, they could increase the percentage of people that find the device initially intuitive. For example, if the designers of the BrainPort (Wicab) could update it, to allow for a greater degree of flexibility as stated here, many potential BrainPort users would likely enjoy gains of the device earlier on in the learning process. Adding further adaptability to any computer interface has untold benefits, and improving the BrainPort will allow for deeper exploration into the cognitive sides of these devices. Using sighted participants in the present experiment has provided a suitable baseline from which to launch a similar protocol with blind persons.

Additionally, to the broader HCI community, our research highlights the general importance of customisable interfaces. Differences in interaction preferences can occur in even the most specific and novel technologies, like the BrainPort. As technologies become more specific, and as tactile methods are introduced into the wider computing industry (for example, feedback in gaming or engineering), it is vital for designers to allow for individual differences by incorporating flexibility in the use of the device.

Conclusion

The research of sensory substitution has much to offer the field of HCI, in the form of maximising information transfer through non-visual displays. Our research into perspective-taking, using the tongue as an interface receptor, shows that when considering tactile displays, it is crucial to strive for the most customisable displays as possible. Factors that contribute to making a device as intuitive as possible can range through personal, interpersonal, and spatial; we tested gender, trait openness and extraversion, and camera orientation. We saw that openness may have played a small role in influencing the adopted perspective, but not to a sufficient degree to explain the observed variation within the sample. Making devices highly customisable would allow for individual differences within a user population, regardless of influencing factors. Specifically, regarding the BrainPort, a simple software update could improve the accessibility for users, particularly in the initial stages of acquiring the device.

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Introduction to Chapter 2

Chapter 1, *Reading with the Tongue: Individual Differences Affect Perception of Ambiguous Stimuli with the BrainPort,* began to investigate some of the very fundamental aspects of interpreting spatialised information on the surface of the tongue. The chapter demonstrates that individual differences may play a role in how spatial information is comprehended, and that even different stimulus types can influence the perspective of the user. We found strong evidence that BrainPort users generally adopted a self-centred perspective in response to ambiguous letter stimuli, but there was a large variation in response to directional arrows. This disparity between stimulus types, in addition to the observed individual differences, strongly emphasises the need for tongue interfaces to be highly customisable and for careful consideration to be made when deciding where information should be displayed on the tongue in relation to external stimuli. This is crucial for sporting contexts, as the cognitive construction of verticality will be implicated in tasks such as obstacle avoidance (e.g., ducking under a low hanging branch while running), or moving through the vertical plane (e.g., moving up a climbing wall).

The experiment in Chapter 1 allowed participants to actively explore the interface for ten seconds before making a spatial judgment. While this is common practice in BrainPort research (Pamir et al., 2019), it does not represent a valid reproduction of a 'real-life' use case, particularly for locomotion, sport, or exercise. To understand a faster pace of perception on the surface of the tongue, we needed to examine the rapid deployment of attention in response to cueing stimuli. Specifically, the Posner Cueing Paradigm has helped to inform our current knowledge of spatial attention in the visual, audio, and tactile modalities (Driver & Spence, 1998; Spence & Gallace, 2007), but has yet to be applied to the tongue. Chapter 2 builds on Chapter 1, continuing the of use psychophysical methods, but this time to explore the orientation of tactile attention on the surface of the tongue in response to both unimodal and crossmodal cues.

Discerning whether tongue interface users can orientate their attention to specific parts of the tongue, in response to cueing information, will play an important role when considering the feasibility of devices, such as the BrainPort, for the purpose of sport. For example, hearing a warning sound (e.g., an approaching vehicle) to one side may draw attention on the tongue to that side. However, if this is not the case, and device users cannot successfully orientate attention to cues, then device designers will need to make technological considerations to draw attention by other means (e.g., using AI to highlight an approaching vehicle).

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Chapter 2 Statement of Authorship

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Statement from Candidate	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.								
Signed	[redacted]			**Date**	10/01/2022				

Chapter 2: Orientation of Tactile Attention on the Surface of the Tongue

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Abstract

The tongue is an incredibly complex sensory organ, yet little is known about its tactile capacities compared to the hands. In particular, the tongue receives almost no visual input during development, and so may be calibrated differently compared to other tactile senses for spatial tasks. Using a cueing task, via an electrotactile display, we examined how a tactile cue (to the tongue) or an auditory cue can affect the orientation of attention to electrotactile targets presented to one of four regions on the tongue. We observed that response accuracy was generally low for the same modality condition, especially at the back of the tongue. This implies that spatial localization ability is diminished either because the tongue is lesser calibrated by the visual modality, or because of its position and orientation inside the body. However, when cues were provided crossmodally, target identification at the back of the tongue seemed to improve. Our findings suggest that, while the brain relies on a general mechanism for spatial (and tactile) attention, the surface of the tongue may not have clear access to these representations of space by itself but can be directed by other sensory modalities.

Keywords: tactile attention; sensory calibration; tongue interfaces; exogenous cueing

Public Significance Statement

This study suggests that, while the tongue is an incredibly sensitive sensory organ to touch sensations, it does not process tactile attention in a uniform way. This has some implications for accessibility devices that use the tongue as a method for interacting with technology. Very little is known about the touch capabilities of the tongue, and these results begin to explore the tongue's attentional processing on its surface.

Introduction

The tongue is complex and has a diversity of sensory and motor capabilities. As well as possessing a greater sensitivity than even the fingertip to pressure and roughness (Miles et al., 2018), tactile and pain thresholds (Okayasu et al., 2014), adaptive viscosity discrimination in response to temperature (Aktar et al., 2015a; Lv et al., 2020), and firmness (Aktar et al., 2015b); the tongue can also sense wetness/dryness, detect taste, and is involved in unconscious movement such as speech, breathing, and swallowing (Dotiwala & Samra, 2018; Haggard & de Boer, 2014; Hiiemae & Palmer, 2003). All of these relatively impressive feats are accomplished with very little influence from the visual system due to its location inside the body (Fujii et al., 2011), unlike the fingertip, for which vision tends to hold precedence over the sensation of touch (Hartcher-O'Brien et al., 2008). Considering the enormous variety of abilities afforded by the tongue, it is surprisingly unstudied in comparison to other body parts (Mu & Sanders, 2010), indeed in two comprehensive reviews of the tongue's somatosensory processing, researchers have independently reflected on both the lack of research, and the variance within conducted research, due to measurement difficulties (Haggard & de Boer, 2014; Sakamoto et al., 2010). Studies that examine the wider capacities of the tongue (past the more biological, and physiological aspects) have mostly focused on its use as a human-computer interaction (HCI) interface, given its sensitivity, for a range of technology. For example, the tongue's effectiveness as an interface for HCI techniques has been tested for wheel chair control (Kim et al., 2013; Lontis et al., 2014, 2016); sensory substitution for the visually impaired (Grant et al., 2018; Lee et al., 2014; Nau et al., 2013; Richardson et al., 2020); vestibular substitution for patients with vestibular loss (Bach-y-Rita et al., 2005; Danilov et al., 2007; Tyler et al., 2003); delivering digital taste sensations (Spence et al., 2017); and personal computer interaction (Dublon & Paradiso, 2012; Huo et al., 2008; Struijk et al., 2009). The benefits of the tongue as an interface are often highlighted by device designers and researchers (Grant et al., 2016; Huo & Ghovanloo, 2010; Van Boven & Johnson, 1994); for example, its wetness is ideal for electrostimulation, with a low two-point touch threshold affording good spatial resolution (Van Boven & Johnson, 1994). In addition, the tongue is located in the head, and thus it is often intact in tetraplegic spinal cord injuries.

The tongue, with a typically horizontal surface close to the body's medial axis, head-based location, and a high grain sensitivity, has a great potential to increase our understanding of how the brain processes spatial information. The examination of mechanisms such as tactile attention and spatial exploration, for example, have been almost exclusively conducted with other parts of the body like the hands (Spence & Gallace, 2007). While tactile attention historically has not received as much recognition as visual attention, in recent years the interest in tactile attention has grown quickly (Anobile et al., 2020; Gillmeister & Forster, 2012; Soto-Faraco et al., 2005; Spence & McGlone, 2001; Tonelli et al., 2019). In particular, research has been focusing on the crossmodal links between tactile and the other senses (Eimer et al., 2002; Eimer & van Velzen, 2002; Spence et al., 2000). What is seen can influence what is heard and felt, and vice versa. Moreover, crossmodal links can not only influence but also enhance information processing between modalities. For instance, even non-informative visual information (such as looking at the back of a hand or the arm) can improve perceptual ability in the tactile modality (Cardini et al., 2012; Marisa et al., 2004).

Key paradigms in the study of attention are the adaptions of the Posner Cueing Task (Posner et al., 1984; Posner & Cohen, 1894), perhaps the most well-known and used spatial cueing task (Posner, 1980; Posner et al., 1980, 1984). At the basic level, the Posner Cueing Task highlights that humans are faster at orientating their spatial attention to an area that was ‘cued’ by previous salient information. The directing (or pre-cueing) of spatial attention can be split between two categories: endogenous and exogenous. An exogenous cue is when an object, or some salient spatial information appears in the periphery of an observed area (be that visually, auditorily, or tactilely), which directs attention to the area in which it appeared. This is opposed to an endogenous cue, which offers a symbolic indication of where attention should be directed. An example of endogenous cueing would be using centrally located arrows on a screen to point to the location of a possible target in the periphery, or hearing the word ‘left’ in both ears (Godijn & Pratt, 2002). In contrast, exogenous cueing would involve presenting a cueing object in the periphery that cues the target by covering the area in which the target may appear, or hearing a tone coming from the left (Posner & Cohen, 1894). Exogenous cueing relies on ‘bottom-up’ processes (Theeuwes, 2004), and how attention is captured by the appearance of new information in the spatial peripheries, whereas endogenous cueing uses ‘top-down’ processes to symbolically direct attention towards a spatial location (Van der Stigchel, Meeter, & Theeuwes, 2007).

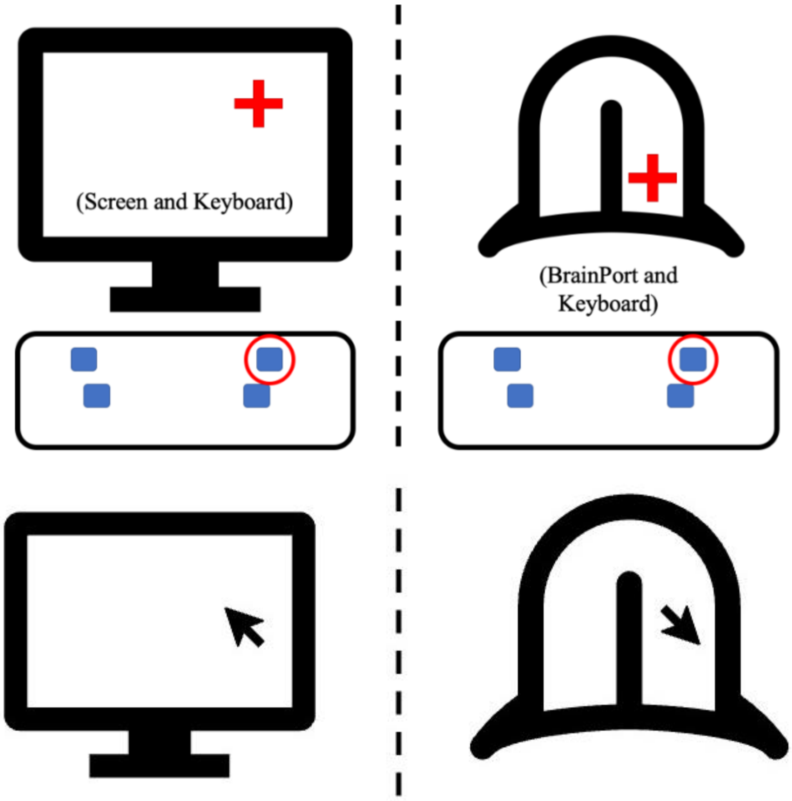
Initial research using the Posner Cueing Paradigm focused on visual attention, yet later work has replicated similar findings in both the auditory and tactile senses, and crossmodally (Driver & Spence, 1998; Hopkins et al., 2017; Spence & McGlone, 2001; Stiles & Shimojo, 2015). For example, to examine whether participants could reflexively orientate tactile attention towards exogenously cued spatial information, Spence and McGlone (2001) used a variant of the Posner Cueing Paradigm. They gave participants a foam cube with vibrating tactors attached to the top and bottom, in each hand. Participants would receive a cue to either the left or right hand with the tactors positioned on the index finger and thumb. The cue consisted of a brief vibro-tactile stimulation to both index finger and thumb at the same time and was followed by a target presented to either the index finger or thumb. The participants' task was to make 'up' or 'down' judgements using a foot pedal as to whether the target was at the top (at the index finger on the cube), or the bottom (at the thumb position on the cube). As the cue was presented to both the index finger and the thumb, it was not spatially predictive of 'up' or 'down', but may coincide (or not) with which hand would receive the target information. Spence and McGlone (2001) found the first empirical evidence that tactile attention, similarly to visual and auditory attention (Spence et al., 1998a; Spence & Driver, 1994), is reflexively drawn to an exogenously cued location.

Examining tactile attention on the tongue by using the Posner Cueing Paradigm may help to better understand whether the brain uses a general mechanism of spatial attention, despite the added complexities and differences of the tongue as a tactile medium. For example, the tongue differs from the hand in its position in space, in its visibility and in its orientation within the body. Moreover, the tongue may raise some interesting questions about the crossmodal construction of space (Eimer & van Velzen, 2002; Spence et al., 2000). For instance, motor control and somatosensory feedback of the tongue are linked with auditory perception through speech, with audio processing regions of the brain coactivating with audio production regions (Hiiemae & Palmer, 2003; Sato, Buccino, et al., 2010; Wilson et al., 2004; Wilson & Iacoboni, 2006). This bares the question of whether these existing links facilitate crossmodal cueing of space. While the interaction between auditory and tactile attention has been examined before (Collignon & de Voider, 2009; Menning et al., 2005; Vercillo & Gori, 2015), and there is consistent evidence that auditory and haptic senses integrate optimally in sighted adult and early blind individuals (Petrini et al., 2014; Scheller et al., 2021), it is still unclear whether these are generalisable to the tongue.

Although using foam cubes to deliver tactile information to the hands is a viable choice for examining tactile spatial construction, it is unfortunately not a feasible choice when studying the tongue. In contrast, the development of tongue interfaces from the field of sensory substitution may offer the required hardware for such a task. Sensory substitution devices (SSDs) translate the information from one modality to another, most commonly from vision into either audio, or tactile feedback (see Kristjánsson et al., 2016, for review). The BrainPort (Wicab, WI, USA) is a vision-into-tactile SSD that uses a tongue interface to convey pixilated information to the user (Danilov & Tyler, 2005; Kaczmarek, 2011), and has the potential to be incredibly useful when studying the spatial organisation of the tongue. For example, Richardson et al. (2020) used the BrainPort to investigate the brain's construction of verticality through the tongue, showing it may be a viable tool to study other aspects of spatial construction. However, a possible issue with the BrainPort, is that it maps the concept of 'up' with the back of the tongue (see Figure 1), which may add a further spatial manipulation and may reduce user competence (Arnold et al., 2016; Arnold & Auvray, 2018; Pamir, Jung, et al., 2020; Richardson et al., 2020). Further, recent work has suggested that the tongue suffers with an information 'bottleneck' at the back, meaning that information presented to the front is a higher fidelity than that of the back (Pamir, Canoluk, et al., 2020). This bottleneck is potentially created by different innervation patterns and densities of receptors across the different regions of the tongue (Trulsson & Essick, 1997); for example there is a higher density of fungiform papillae towards the tip of the tongue, which is associated with increased electrotactile discrimination (Allison et al., 2020). However, Pamir and colleagues (2020) only explored spatial pattern recognition on the tongue, and not whether this informational bottleneck impinges more general attentional deployment at the back of the tongue. When substituting visual information into another modality, sensory overload may also be a factor in spatial processing as vision is an incredibly high bandwidth sense (Richardson et al., 2019). There is an ongoing discussion in the field of sensory substitution concerning the potential of sensory overload and how to minimise it (Brown et al., 2014; Elli et al., 2014; Haigh et al., 2013; Kristjánsson et al., 2016; Shull & Damian, 2015). However, a conclusive method for maximising device comprehension while remaining under the overload threshold has yet to emerge. Theories from multisensory integration and information redundancy may hint that providing the same information via two modalities may offer a more reliable perception, particularly for older adults (Laurienti et al., 2006). For example, learning the location of objects captured by a camera and represented by a SSD as something heard or touched might benefit from also experiencing it via self-motion. However, offering multisensory information redundancy via sensory substitution does not appear to offer any notable gains (Jicol et al., 2020), and recent research into crossmodal perceptual load hints that limitation may exist at the unimodal level rather than at a supramodal level (Sandhu & Dyson, 2016). Other methods could involve multisensory cooperation instead (Lloyd-Esenkaya et al, 2020), where different aspects of an image of an object might be easier to understand by splitting sensory information between modalities providing different components to the auditory and tactile senses, such as location and identity. It is currently unknown whether the orientation of attention through a SSD can be influenced by the remaining modalities, or whether splitting information between the modalities can improve spatial orientation to any measurable degree.

Figure 1

Demonstrating the BrainPort's translation of vertical space to the tongue.



Note. (Top) The left side of the figure demonstrates a task in which a person must look at a screen displaying a cross and press a corresponding key to judge whether the cross is up or down and left or right. The right side of the image shows the identical task but as perceived through the BrainPort. Although the cross is presented to the top of the BrainPort's camera's field of view, it corresponds to the back of the tongue. (Bottom) The left side of the figure demonstrates a task in which a person must move the mouse to the top of the display. The right side shows how this task would appear on the tongue if the person was perceiving the display through the BrainPort.

The present study aimed to explore deployment of tactile attention on the surface of the tongue, in response to exogenous cues and examine whether the bottom-up attentional prioritisation found in other sensory systems is present and extends to such a complex sensory organ, thus pointing to a general attentional mechanism. The study was inspired by the work of Spence and McGlone (2001), and we kept it as similar as possible to allow for tentative comparisons with their findings using the hands. We collected data over two experiments, and then split the analysis into three sets. The first focused solely on tactile attention, hence both the cues and the targets were presented to the BrainPort and, therefore, participants were required to only attend to the tongue. The second explored the influence of crossmodal auditory cueing on tactile attention via the BrainPort, hence while the cues were auditory the targets were presented to the BrainPort and, therefore, participants had to attend to two types of stimulus modality. The second aimed to explore how the exogenously cued spatial attention on the tongue was influenced by crossmodal auditory information. The third compared the results of the unimodal condition with the results of the crossmodal condition. As the tongue does not have a uniform sensitivity across the surface, instead of using pure left verses right judgements, we divided targets between four quadrants, to further explore the findings of Pamir et al. (2020) and examine whether the informational bottleneck at the back of the tongue also inhibits attention prioritisation in response to exogenous cues. In both experiments we collected data on reaction time of correctly answered trials, and accuracy (the proportion of correct responses). We also aimed to explore whether, when using the BrainPort as a computer interaction method, tactile attention improved by having response keys matched to either the screen or the tongue, by inverting the response keys.

We hypothesised that trials that presented the cueing stimulus and the target in the same side of space (ipsilateral trials) would be significantly faster in reaction time to those trials for which the cue and target stimulus were presented in different sides of space (contralateral trials). We also expected targets that were presented to the tip of the tongue would elicit faster and more accurate responses than targets at the back of the tongue due to a higher density of innervation (Allison et al., 2020; Trulsson & Essick, 1997). We initially expected that using an auditory cue rather than a tactile cue to direct tactile attention on the tongue would improve task performance by reducing the load on any one sense due to perceptual overload potentially occurring at the modality level (Sandhu & Dyson, 2016); albeit a cautious hypothesis as the research on crossmodal sensory substitution is varied (Jicol et al., 2020; Maidenbaum et al., 2014; Shull & Damian, 2015). Finally, we hypothesised that mappings between the tongue and the keyboard would be more effective than mappings between the screen and the keyboard when using the BrainPort.

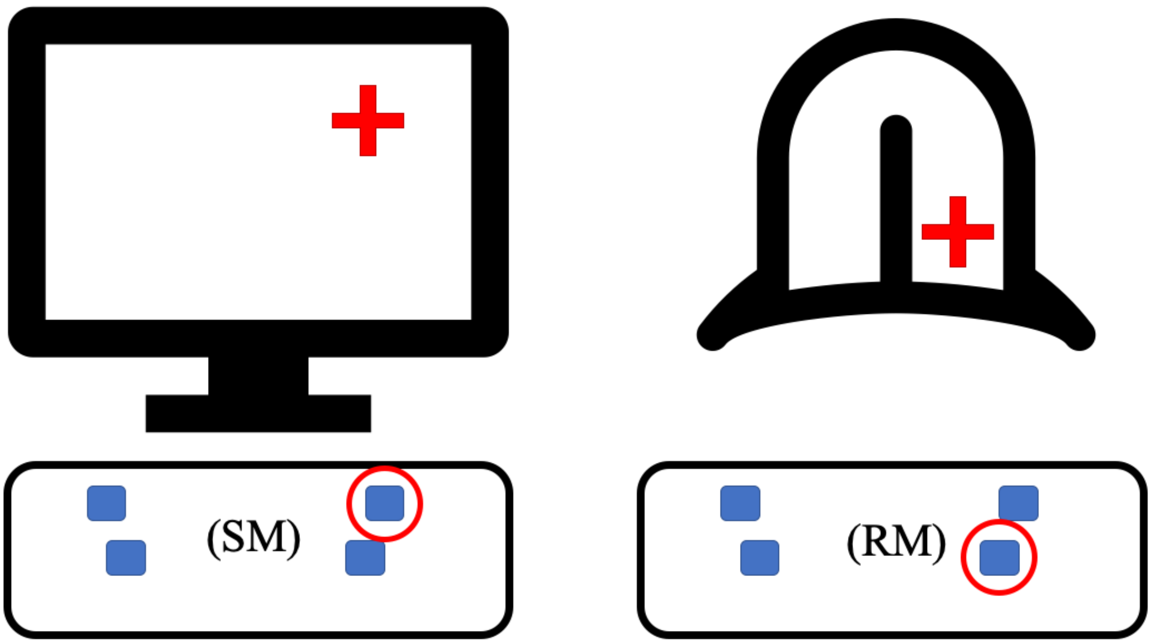
Methods

Design

Here we report the results of two experiments split up into three main analysis sets, one for each modality cue condition, and one to compare the results of each modality. The first provided cues and targets directly on the tongue via the BrainPort (tactile cues). The second continued to provide targets to the tongue, but offered auditory cues. The third compared the results of the two experiments. All of the cues were only informative about the side (left or right) of a possible target appearance and did not inform on whether the target would appear at the top or bottom of the screen. In each experiment participants were randomly assigned into one of two further keyboard mapping groups, either standard mapping or reversed mapping. In the standard mapping groups the response buttons' positions corresponded to the target position on the screen, and the typical BrainPort arrangement; information at the top of the camera's field of view paired with 'back of the tongue' responses. In the reversed mapping conditions, the response buttons' positions corresponded to the target position on the tongue, with information appearing at the top of the camera's field of view paired with 'tip of the tongue' responses (see Figure 2); the spatial information aligned along the sagittal plane, moving out from the midline of body.

Figure 2

Demonstrating how to use the BrainPort as a computer interaction method.



Note. This figure shows a target presented to the top right of computer screen and how this spatial information would appear on the tongue display of the BrainPort. The keyboard on the left shows which button should be pressed in the standard mapping (SM) condition, and the keyboard on the right shows which button should be pressed in the reversed mapping condition.

The unimodal tactile cueing analysis and the audio crossmodal cueing analysis both had three factors. The first factor was spatial cueing, and had two levels, ipsilateral (cue predicted location of target) and contralateral (cue did not predict location of the target) trials. The second factor was the effect of the delay between the cue and target or stimulus onset asynchronies (SOA), using the same lags (200 ms, 300 ms, and 400 ms) as in Spence and McGlone (2001). We chose these SOAs as to maintain similarity to Spence and McGlone's (2001) study, and to allow for further exploratory analysis of any impact of SOA on cue enhancement or inhibition (Klein, 2000; Posner et al., 1985; Spence et al., 2000). The third factor was the target location on the tongue, and had four levels, tip right, back right, tip left, or back left of the tongue. Two dependent variables were analysed, reaction time (RT) for correctly answered trials, and the proportion of correct responses, or accuracy. The data of these two analyses were also compared together, after looking first at unimodal tactile cueing responses, and crossmodal audio cues.

Participants

Participants were recruited via internal communications at the University of Bath. Twenty participants took part in each experiment, tactile (mean age = 24.1 ± 4.3 years; 15 female), and audio (mean age = 20.7 ± 1.3 years; 16 female), that is, 40 participants in total. This sample size was chosen due to factors of limited time and resources, and, using Spence and McGlone's (2001) recruitment of six participants as a starting point, rounding up our number of participants to 10 per between-subject group. As such, we emphasise that readers should consider the effect sizes over *p*-values when evaluating the results (Lakens, 2021). Prior to starting the experiment, all participants were given an information sheet about the nature of the study and provided written informed consent. Ethics was granted by the Department of Psychology Research Ethics committee, University of Bath [reference no: 19: 061]. Participants in the tactile experiment received a £5 voucher after completing the study. All participants had normal, or corrected to normal vision, and reported no other sensory impairments.

Materials and Measures

The BrainPort Vision Pro (Wicab, WI, USA) was used in the experiment. This is an updated version of the device and as such, is underrepresented in peer reviewed articles, with most of the prior BrainPort research featuring the V100 – which used a camera mounted on a pair of sunglasses as the sensor (e.g., Grant et al., 2016). The Vision Pro is a fully integrated, stand-alone unit (see Figure 3) that has an adjustable camera mounted on the forehead, a battery pack and processer at the rear, and a 394-electrode array that forms the inter-oral display (IOD). The IOD is 29.5 × 33.8 × 7 mm in size, and the electrodes are spaced at 1.32 mm from centre to centre (Grant et al., 2018). The BrainPort can vary the strength of its stimulation from 0 to 17 V at 100% intensity, we found from verbal feedback during previous research that most participants found that an intensity of 60% was comfortable while still maintaining a clear representation of information (Richardson et al., 2020). We therefore initially set the device at 60% but adjusted it from there to each participant's particular comfort. The camera's field of view (FoV) on the BrainPort can be adjusted between 3° and 47°, for this study, the FoV was set at 47° as the BrainPort's placement was set up close to the screen (30 cm between BrainPort camera lens and the monitor). To completely eliminate any movement while participants were using the BrainPort, it was mounted on a mannequin head and participants sat next to the head with the IOD on their tongue; this ensured that the camera was always the same fixed distance from the screen, and therefore, the sizes of the cues and stimuli were fixed (moving closer to the screen would make the stimuli appear larger).

Figure 3

The BrainPort sensory substitution device positioned on a mannequin's head.

The experiment was initially built in the PsychoPy builder (Peirce et al., 2019), then adapted by editing the outputted Python (Version 3) code. For additional stimuli details please refer to the supplementary materials. The experimental programme was run on a

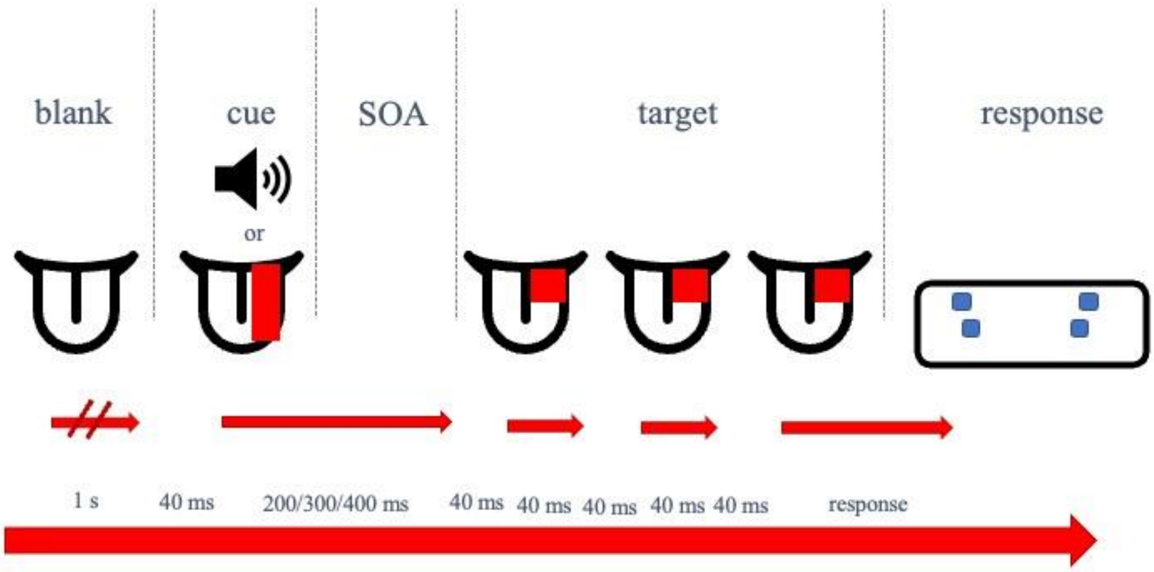
MacBook Pro (Early 2013 model, Apple, USA) with a 2.7 GHz Dual-Core Intel i5 processor and 8 GB of DDR3 RAM. In the audio experiment, the auditory cues were delivered through headphones (HD 202, Sennheiser, Germany). The tactile target consisted of a triple pulse of 40 ms exposure to one of the four corners of the tongue, separated by a 40 ms gap, similarly to Spence and McGlone (2001).

Procedure

Participants first were given the experiment description and were asked if they had any questions about the study. Next participants provided informed consent and were led into the experimental room and sat on a chair. The participants could then pick up the IOD to familiarise themselves with the design, and experience how it felt when on the tongue. The information being stimulated through the IOD at this stage was instructional writing on the screen for the benefit of the researcher, so when the participant initially made tongue contact with the electrodes, they received some electrical feedback, but it was not overwhelming; as the BrainPort provides a truly novel experience, initial contact can be surprising. Once the participant was completely comfortable with holding the IOD on their tongue while holding their hands over the response keyboard, the training process commenced. The first part of the training was device and response familiarisation. Participants would receive constant stimulation to one of the four corners of the tongue and then were required to press the key that corresponded to the tactile sensation on the tongue. The trial would not move on until they had selected the correct key. This was to ensure that the participant understood the mappings between tongue sensation and the corresponding key (see Figure 2). There were eight trials in total in this phase, two for each corner of the tongue. Participants were also given examples of the cues at this stage. For the tactile experiment the entire left or right side of the tongue was stimulated, and the researcher verbally asked the participant where they could feel stimulation. For the audio experiment training phase, five cues were played to each ear, with a pause for the researcher to enquire whether the participant had heard the cues and could spatially differentiate between the left and right presentations. The next section of training completely mimicked the full experiment, but with one block of 24 trials (8 repetitions × 3 SOAs, split evenly between the different locations of the tongue and balanced between contralateral and ipsilateral trials), which took around one minute to complete. The participants were blindfolded at this stage, rather than earlier, to allow participants to familiarise with the device and control for any discomfort before continuing. At this point participants were already familiar with the room, headphones, and IOD before experiencing the blindfold. Once the participant had completed the practice block, they could remove the blindfold, headphones, and IOD to rest and ask any further questions. The researcher could also provide some minor feedback from the practice trials at this stage (e.g., offering a reminder for which part of the keyboard corresponded to the spatial location on the tongue).

Figure 4

Trial configuration of the tactile and auditory experiments.



Note. The tactile cue and target resulted from the transfer of the visual information on the screen (i.e., white rectangle on the black screen) to the tactile information on the tongue, however because participants were blindfolded, for simplicity we call this information tactile. Each trial was constructed identically in each experiment except for the cue, which changed depending on the experiment. SOA: Stimulus onset asynchrony.

After resting, the participant completed the two main experimental blocks, which consisted of 144 trials each, this mirrored the number of trials used by Spence and McGlone (2001) in the hope it would provide some comparability. Each participant completed 288 trials in total, which were equally split between ipsilateral and contralateral trials, and further divided by the three different SOAs (200 ms, 300 ms, and 400 ms, respectively), and again by target location (tip right, tip left, back right, back left); trials were presented in a randomised order. Participants could rest between the blocks for as long as they felt necessary, and when they completed the final block, the researcher provided the participant with a debrief and another opportunity to ask questions. The experiment took roughly one hour in total to complete, including training and practice trials.

Data Analysis

Prior to statistical analysis, data were visually checked for outliers or errors in entry. Each participant's individual data were collated onto spreadsheets, and mean scores were calculated for accuracy and reaction time. Outliers were identified, and removed, on the basis of being 3 standard deviations away from the z score. A total of 101 trials were removed from the dataset, which accounted for less than 1% of the trials. Upon looking at each individual participant's performance, it was clear that one participant (in the audio standard mapping group) may have not understood the task instructions as they only answered 26 of 288 correctly, the next lowest in the same group was 179 of 288; therefore, the participant was removed from analysis. Additionally, four participants had to be removed solely from the tactile reaction time analysis, as they failed to answer any trials correctly for certain combinations of factors (see Figure S1 in supplementary material). The reaction time analysis in the tactile condition should therefore be treated with some caution, and we emphasise considering the effect sizes. After removing outliers and incorrect trials (for the reaction time analysis), other assumptions were checked. See the supplementary material for the relevant assumption checks required for performing an analysis of variance (ANOVA) test.

The first analysis was on the tactile data, combining both keyboard mappings into one group. A three-way repeated measures ANOVA was used to examine the factors of spatial cueing (ipsilateral verses contralateral cued trials), SOA (200 ms, 300 ms, and 400 ms), and target location (tip right, tip left, back right, and back left) on the dependent variable of reaction time, and another three-way repeated measures ANOVA, with the same factors examined the dependent variable of accuracy (measured as the proportion of correct responses). The second analysis examined audio cueing and used the same format as the tactile data; two three-way repeated measures ANOVAs with the dependent variables of reaction time, and accuracy, respectively. The third analysis used two two-way between subject ANOVAs (on the dependent variables of reaction time and accuracy again), comparing the factors of cueing modality (tactile cues versus audio cues), and keyboard mapping (reversed mapped versus standard mapped). If any significant effects were found from the omnibus tests, then follow up Bonferroni corrected t-tests were used to further explore differences, providing the results addressed a hypothesis. We focus on these factors and analyses (rather than conducting five-way mixed ANOVAs) for two main reasons. First to allow for a more direct comparison between the present study findings using the tongue and those of Spence and McGlone's (2001) using the hands. Secondly, to reduce the complexity of the interaction effects in the hope of more interpretable results as we do not have predictions for the higher-level interactions.

Data were recorded from PsychoPy as *.csv* files and pre-processing was conducted using NumPy (Version 1.17.2), Pandas (Version 0.25.1), and Pingouin (Version 0.3.5) libraries for Python. Analysis was conducted in R, using the *ezANOVA* package (Version 4.4.0), and data visualisations were created using *ggplot2* (Version 3.3.3) and *ggpubr* (Version 0.4.0) packages. Tables of participant mean RT and accuracy scores were created in Microsoft Excel (Version 16.37) as pivot tables for ease of data exploration. See the supplementary material for the analysis code script.

Results

Analysis Set 1:

Reaction time and accuracy in response to unimodal tactile cues

In the reaction time analysis, there was only a significant main effect for target location. The main effect of SOA was non-significant, as was cueing, and the interactions between SOA and spatial cueing; SOA and target location; spatial cueing and target location; and the three-way interaction between SOA, spatial cueing, and target location (See Table 1 for ANOVA results). To follow up on the significant effect for target location, pairwise t-tests with Bonferroni corrections were used to compare mean reaction times. Targets appearing on the tip right of the tongue were significantly faster than the back left (p = .003, d = .188), but not the back right (p = .277, d = .111), and targets on the tip left were also significantly faster than the back left (p < .001, d = .629), and back right (p < .001, d = .320). Targets on the tip left were not significantly faster than the tip right (p = 1, d = .069), and targets on the back left were not significantly faster than the back right (p = 1, d = .105). See Figure 5A for boxplots showing target location with SOA for the average reaction times. Also see Table S1 in the supplementary material for exact means and standard deviations.

Table 1

ANOVA results for reaction time in the unimodal tactile condition.

	F	*df1*	*df2*	*p*	η^2
Target Location	7.46	2.20	33.03	.002	.035
SOA	.39	1.44	21.60	.615	.001
Cueing	.20	1.00	15.00	.659	< .001
SOA × Cueing	1.14	2.00	30.00	.334	.002
SOA × Target Location	.50	2.16	32.00	.627	.004
Cueing × Target Location	.63	3.00	45.00	.599	.002
SOA × Cueing × Target Location	.56	2.78	41.76	.631	.003

Note. SOA = Stimulus Onset Asynchrony

For accuracy, there was only a significant main effect for target location. The main effect of SOA was non-significant, as was the effect of cueing. The only significant interaction was between SOA and target location. The interaction between SOA and spatial cueing was non-significant, as was the interaction between spatial cueing and target location, and the three-way interaction between SOA, cueing, and target location (for ANOVA results see Table 2). Follow up pairwise comparisons of target locations were carried out, and demonstrated that targets appearing on the tip right of the tongue were responded to significantly more accurately than the back right ($p < .001$, $d = 1.064$), and back left ($p < .001$, $d = 1.206$); similarly, front left targets were significantly more accurate than back right targets ($p < .001$, $d = 1.175$), and back left targets ($p < .001$, $d = 1.307$). There were no significant left versus right differences for the tip ($p = .980$, $d = .172$), or the back ($p = 1$, $d = .143$) of the tongue. See Figure 5B for boxplots showing target location and SOA for the accuracy scores.

Table 2

ANOVA results for accuracy in the unimodal tactile condition.

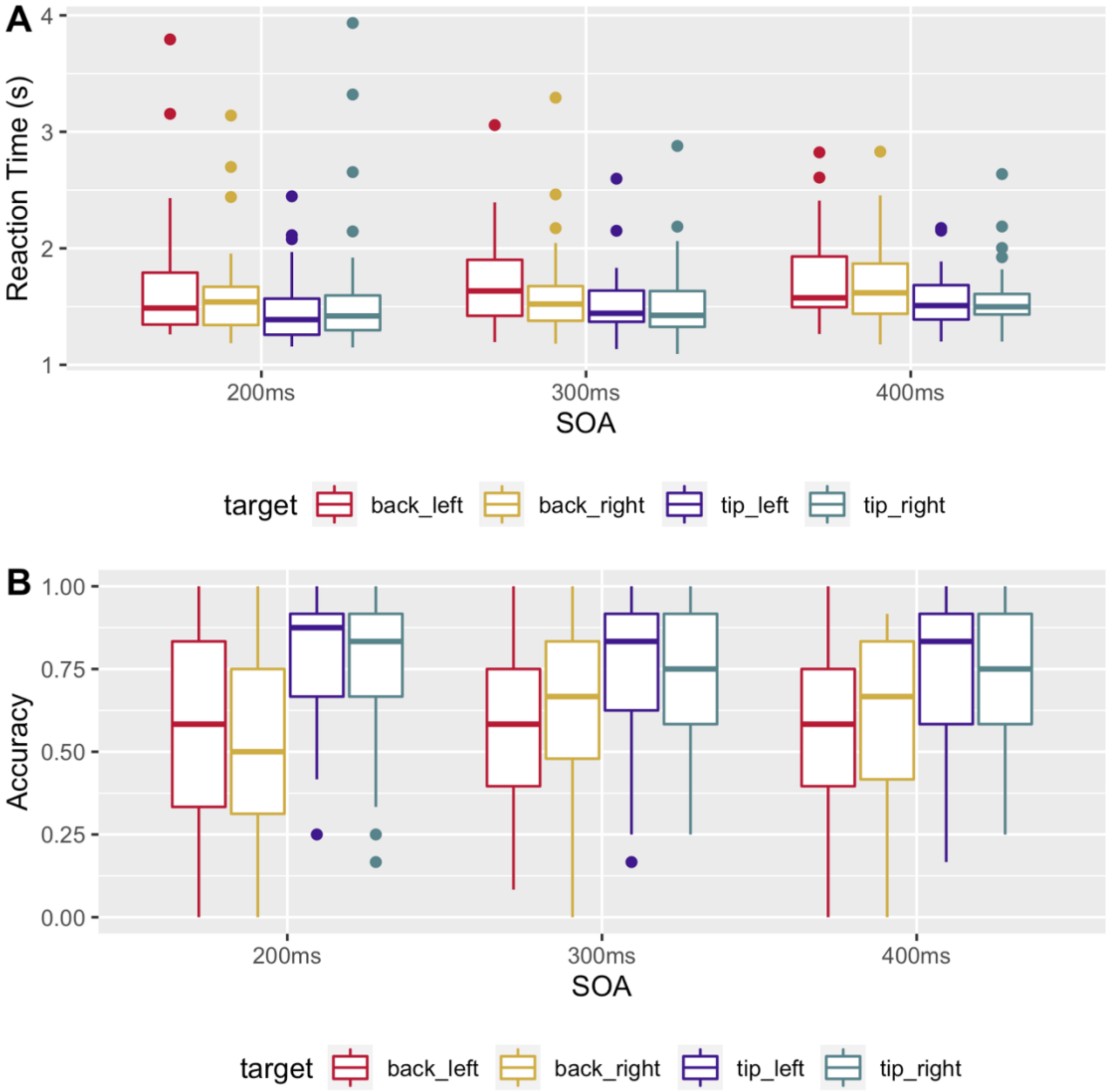
	F	*df1*	*df2*	*p*	η^2
Target Location	8.99	2.03	38.48	< .001	.140
SOA	.14	2.00	38.00	.870	< .001
Cueing	1.57	1.00	19.00	.226	.003

	F	$df1$	$df2$	p	η^2
SOA × Cueing	.12	2.00	38.00	.884	< .001
SOA × Target Location	3.79	6.00	114.00	.002	.012
Cueing × Target Location	.12	3.00	57.00	.946	< .001
SOA × Cueing × Target Location	.81	6.00	114.00	.561	.002

Note. SOA = Stimulus Onset Asynchrony

Figure 5

Results of the tactile cueing modality analysis: plotting target location and stimulus onset asynchrony (SOA).



Note. A = boxplots showing individual reaction time mean scores of each participant, lower scores are better; B = boxplots showing individual mean proportion of correct responses (Accuracy) of each participant, higher scores are better. Upper and lower sections of the box correspond to 25th, and 75th percentiles, respectively; top and bottom whiskers correspond to highest and lowest value up to 1.5 times the interquartile range.

Analysis Set 2:

Reaction time and accuracy in response to crossmodal auditory cues

For reaction time, there was a significant main effect of SOA and for target location, however, cueing was non-significant. The interaction between SOA and target location was statistically significant. All other interactions were non-significant: SOA and spatial cueing; spatial cueing and target location; and SOA, spatial cueing, and target location (see Table 3 for ANOVA results). To follow up the significant main effect of SOA, pairwise comparisons found that 200 ms led to faster reaction times than 300 ms ($p < .001$, $d = .324$), and 400 ms ($p < .001$, $d = .547$), and that 300 ms also led to faster reaction times than 400 ms ($p < .001$, $d = 233$). For target location, tip right targets were significantly faster than back right targets ($p = .001$, $d = .229$), and back left targets ($p < .001$, $d = .296$), as were tip left targets to back right targets ($p < .043$, $d = .181$), and targets appearing at the back left of the tongue ($p < .001$, $d = .256$). There were no significant differences between left versus right for the tip ($p = 1$, $d = .066$), or the back ($p = .775$, $d = .073$). See Figure 6A for boxplots showing target location and SOA for reaction times. Also see Table S2 in the supplementary materials for means and standard deviations in the auditory cueing modality group.

Table 3

ANOVA results for reaction time in the crossmodal auditory condition.

	F	*df1*	*df2*	*p*	η^2
Target Location	7.84	3.00	54.00	< .001	.032
SOA	49.23	2.00	36.00	< .001	.089
Cueing	.07	1.00	18.00	.789	< .001
SOA × Cueing	.67	2.00	36.00	.518	.002
SOA × Target Location	2.75	6.00	108.00	.016	.013
Cueing × Target Location	.27	3.00	54.00	.848	< .001
SOA × Cueing × Target Location	.42	6.00	108.00	.862	.002

Note. SOA = Stimulus Onset Asynchrony

When examining accuracy, the only significant main effect was for cueing, with ipsilateral (.83 ± .38 proportion correct) trials being responded to more accurately than contralateral (.80 ± .40 proportion correct) trials, SOA was non-significant, as was the main effect of target location. All interaction effects were non-significant: SOA and spatial cueing; SOA and target location; spatial cueing and target location; and SOA, spatial cueing, and target location (see Table 4 for ANOVA results). See Figure 6B for boxplots showing SOA with target location for accuracy scores. As cueing demonstrated a small, but significant, effect for accuracy we included an additional figure in the supplementary materials showing SOA with cueing (see Figure S3 in the supplementary materials).

Table 4

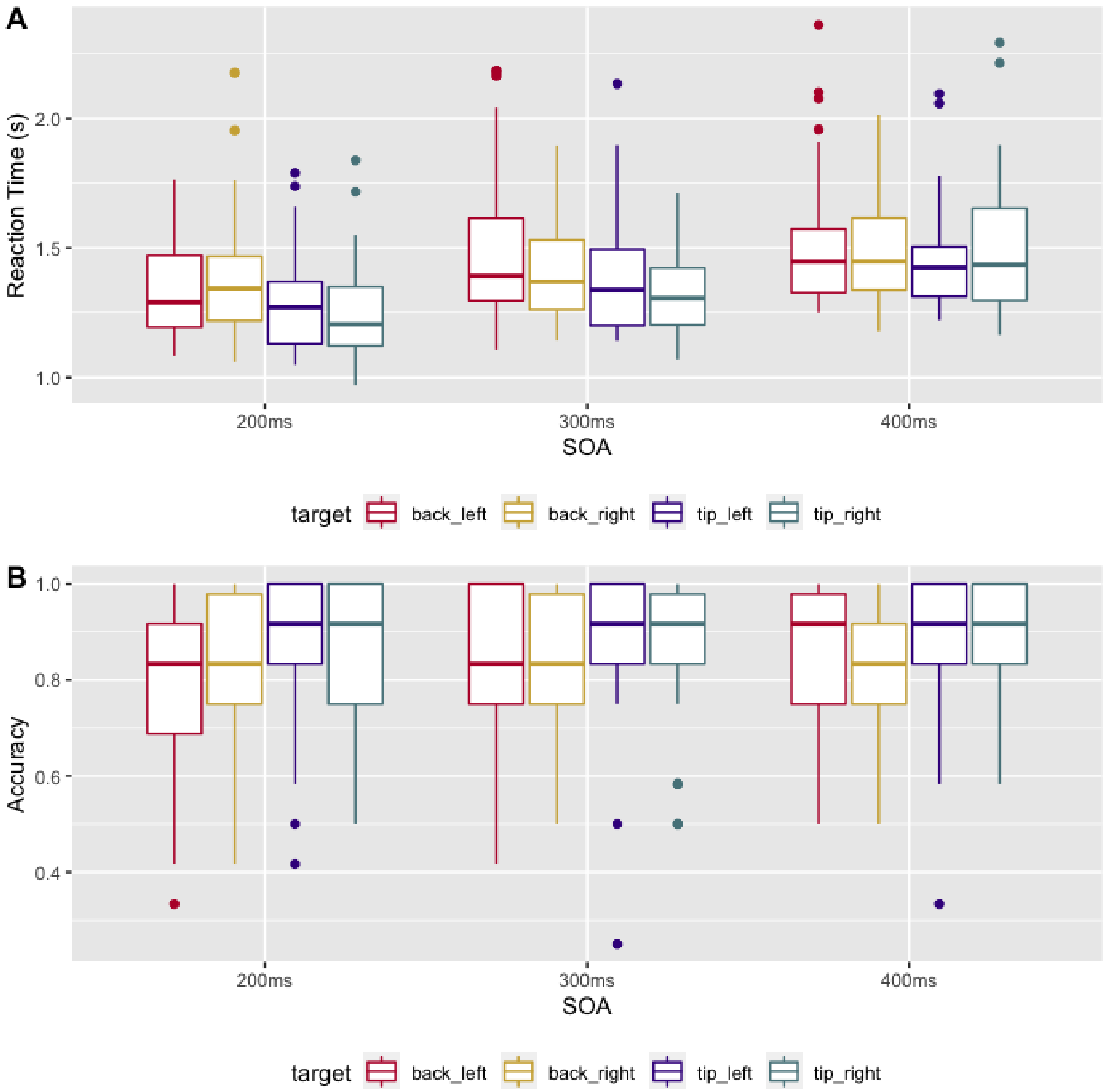
ANOVA results for accuracy in the crossmodal auditory condition.

	F	*df1*	*df2*	*p*	η^2
Target Location	1.34	3.00	54.00	.271	.021
SOA	1.45	2.00	36.00	.248	.002
Cueing	4.54	1.00	18.00	.047	.006
SOA × Cueing	1.58	2.00	36.00	.220	.004
SOA × Target Location	.44	6.00	108.00	.848	.002
Cueing × Target Location	.26	3.00	54.00	.856	< .001
SOA × Cueing × Target Location	.07	6.00	108.00	.999	< .001

Note. SOA = Stimulus Onset Asynchrony

Figure 6

Results of the audio cueing modality analysis: plotting target location and stimulus onset asynchrony (SOA).



Note. A =boxplots showing individual reaction time mean scores of each participant, lower scores is better; B = boxplots showing individual mean proportion of correct responses (Accuracy) of each participant, higher scores are better. Upper and lower sections of the box correspond to 25th, and 75th percentiles, respectively; top and bottom whiskers correspond to highest and lowest value up to 1.5 times the interquartile range.

Analysis Set 3:

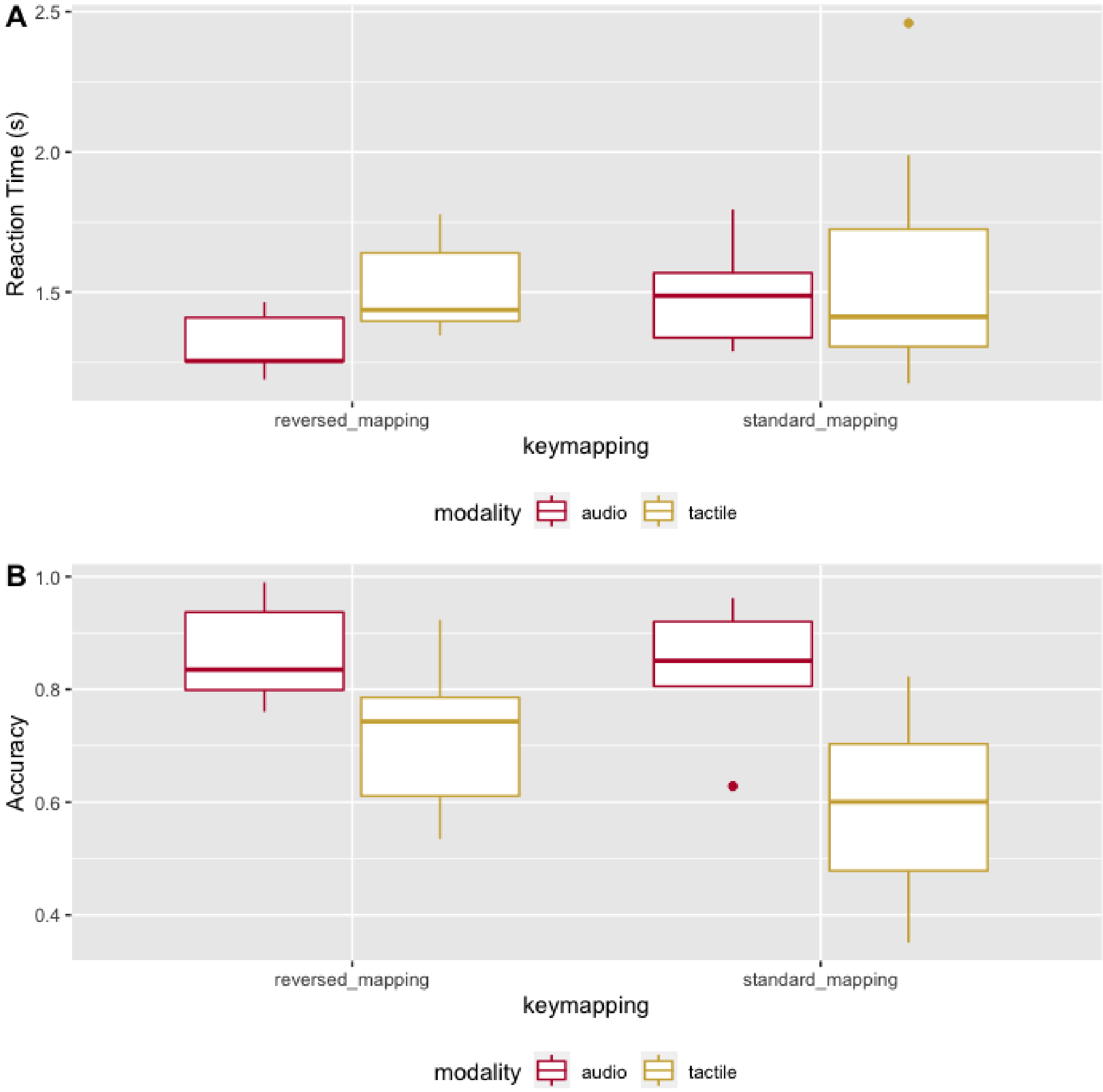
Comparing between audio and tactile cueing modalities and keyboard mapping

For RT, no significant effect was found for the factor of cueing modality ($F(1, 35) = 3.05$, $p = .089$, $\eta^2 = .080$), keyboard mapping ($F(1, 35) = 2.35$, $p = .134$, $\eta^2 = .063$), and interaction between cueing modality and keyboard mapping ($F(1, 35) = .59$, $p = .447$, $\eta^2 = .017$). See Figure 7A for mean reaction times for keyboard mapping and cueing modality.

For accuracy, a significant effect of cueing modality ($F(1, 35) = 23.98$, $p < .001$, $\eta^2 = .407$) was found with higher accuracy for auditory cues versus tactile cues, but not of keyboard mapping ($F(1, 35) = 3.37$, $p = .075$ $\eta^2 = .088$), and of interaction between cueing modality and keyboard mapping ($F(1, 35) = 2.01$, $p = .165$, $\eta^2 = .054$). See Figure 7B for mean accuracy scores for keyboard mapping and cueing modality.

Figure 7

Results of the between group analysis: plotting cueing modality and keyboard mapping.



Note. A = boxplots showing individual reaction time mean scores of each participant, lower scores are better; B = boxplots showing individual mean proportion of correct responses (Accuracy) of each participant, higher scores are better. Upper and lower sections of the box correspond to 25^{th}, and 75^{th} percentiles, respectively; top and bottom whiskers correspond to highest and lowest value up to 1.5 times the interquartile range.

It should be noted that the reaction time analysis in the tactile cueing modality was treated cautiously, as the general level of accuracy was low. Spence and McGlone (2001) discarded participant data when under 85% correct; we did not choose to do this as almost all participants in the tactile cueing group did not pass this threshold, indeed, with some participants failing to respond correctly to any trials when targets were located at the back of the tongue. Therefore, while caution was used when considering the reaction time results, the accuracy analysis may offer deeper insights into performance when both cue and target were presented to the tongue.

Discussion

In the present article we explored the orientation of tactile attention on the surface of the tongue, in response to tactile (same modality) and auditory (crossmodal) exogenous cues. The tongue may represent a higher fidelity, and more complex, sensory organ than the fingertip (the hands being a more commonly used sensory organ to test tactile attention), as the tongue has been shown to possess a finer sensitivity to a range of tactile stimulation (Aktar et al., 2015a, 2015b; Miles et al., 2018; Okayasu et al., 2014). Specifically, we used a variation of the Posner Cueing Task (Posner, 1980; Posner et al., 1984), through the ‘BrainPort’ (a vision-to-tactile device), to examine whether participants could orientate their tactile attention on the tongue in response to tactile and auditory exogenous cues (bottom-up sensory information that directs attention by briefly appearing in the periphery). We also examined the effect of spatial mappings and the tongue’s sensitivity by manipulating keyboard response button mappings (e.g., do keys located at the top of the keyboard better map to the tip of the tongue, or the top of the screen on which the stimuli are presented?), and testing the tongue by dividing it in four quadrants.

In the unimodal tactile analysis, the only significant factor was target location. For both the reaction time analysis, and the accuracy analysis, participants responded to targets that were presented to the tip of the tongue significantly faster and more accurately than targets that were presented to the back of the tongue. There were no left versus right differences for either the tip of the tongue, or the back, in both the reaction time analysis or the accuracy analysis. For the crossmodal auditory-tactile reaction time analysis, a similar result was found, with the addition of SOA also being a significant factor; participants responded quickest to SOAs of 200 ms, then 300 ms, then 400 ms. Targets that were presented to the tip of the tongue were responded to significantly faster than targets presented to the back. There were also no laterality differences for either the tip or the back of the tongue. For the crossmodal accuracy analysis, the only significant factor was cueing, with ipsilateral trials being slightly more accurate than contralateral trials. For the third analysis, that compared the results between the unimodal condition and the crossmodal condition, there was no significant effect found for the reaction time analysis. However, crossmodal audio cues did result in significantly more accurate results than unimodal tactile cues. There was no significant effect for keyboard mapping. The most consistent of these findings, are the stark differences between the tip of the tongue compared to the back, which met our expectations that the higher innervation densities present at the tip of the tongue would result in enhanced cueing effects.

We initially predicted that ipsilateral trials (the cue and the target are on the same sides) would be significantly faster than contralateral trials (the cue and the target are different sides) when all the spatial information was provided to the tongue via the BrainPort, in the *tactile* condition; much in the same way that Spence and McGlone (2001) used foam cubes to provide cue and target information to the hands. However, we did not find any effect of cueing on participants' reaction time when locating the target on the tongue with both ipsilateral and contralateral cues contributing to similar reaction times. This result did not support our first hypothesis and was in contrast with the results of Spence and McGlone (2001) who found a very clear effect of cueing on tactile attention when using the hands, showing that participants were faster when the cue appeared in the same side as the target. One possible explanation for this difference between the hands and the tongue may be due to the hands having a greater representation for laterality in the brain (Ehrsson et al., 2003). The tongue is very close to the mid-line of the body and the distinction between left and right may not be as well represented as it is for the hands. The motor repertoires of the tongue and hands are also quite different, with the hands very much operating in lateral space. Conversely, the majority of the sensorimotor duties performed by the tongue are along the midline (such as most vocal movements and swallowing food), with possible exceptions such as checking one's own teeth (Hiiemae & Palmer, 2003). Additionally, unlike the hands, the tongue is rarely influenced by vision. In neurotypical development, the visual modality helps to calibrate spatial mappings of the other senses (Ernst & Banks, 2002; Gori, 2015; Gori et al., 2010); and, in the complete absence of vision (e.g., in the congenitally blind), tasks such as sound localisation become severely impaired due to lack of calibration (Gori et al., 2014). This may also be the case for the spatial mappings on the surface of the tongue, as with almost no visual calibration of spatial mappings during development, our participants may struggle to accurately orientate to even basic tactile cues. However, other body parts that cannot usually be seen without a reflective surface (such as the face and neck) have demonstrated reliable tactile cueing ability, but with stronger effects for body parts that are more familiar (i.e., the face rather than the neck; Tipper et al., 1998, 2001). The tongue, which is perhaps lesser seen than the neck, may be situated much further down on an exogenous tactile attention continuum. Taking the results from the unimodal tactile condition in isolation, it would first appear that the general mechanism of spatial attention subserving other body parts (Kennett et al., 2001; Spence & McGlone, 2001), may not be generalisable to the tongue.

Interestingly, accuracy greatly improved when the cues were provided crossmodally via the auditory modality compared to unimodally in the tactile sense; and reaction time showed a small, but non-significant, improvement. These results are somewhat more akin to past works on crossmodal cueing (for review see Driver & Spence, 1998), than the unimodal tactile condition. Most participants tended to show a high level of accuracy, however, reaction times were slower than others have reported when using the hands to examine tactile attention (Eimer & van Velzen, 2005; Kennett et al., 2002; Spence et al., 1998b). There is evidence of audio-tactile links in the crossmodal construction of space in the brain, for instance, tactile cues can direct audio attention (Menning et al., 2005), and redundant auditory and tactile size information integrates to form a more accurate perception in adults (Petrini et al., 2014). Here, accuracy data, but not reaction time responses, also showed a significant effect for cueing; the ipsilaterally cued trials offered a slightly more accurate performance. Past research using crossmodal cueing paradigms, tend to show that accuracy is generally stable in response to ipsilateral and contralateral trials (Eimer & van Velzen, 2002; Kennett et al., 2002; Spence et al., 1998b), i.e., while an individual may not respond as quickly to a contralateral trial, they still respond correctly. In the present study, the participants struggled to orientate attention on the surface of the tongue in response to tactile cues, but auditory cues may help to prioritise attention to the correct side. This suggests that although the brain may use a general mechanism of spatial attention, perhaps the tongue as a receptor has a somewhat limited access to this representational information, but attention can be directed by other modalities crossmodally. Perhaps, the strong audio-tactile links that naturally develop during feeding may drive the improved cueing capacity in the crossmodal analysis (Dijk et al., 2013; Spence, 2015; Zampini & Spence, 2004).

While the general lack of a strong ipsilateral versus contralateral effect in reaction time was surprising, we did find, however, a very clear difference between the spatial attention at the tip of the tongue compared to the back. Targets that appeared on the tip of the tongue led to quicker reaction times both crossmodally and unimodally, and more accurately unimodally. Past work identified that fungiform papillae density correlates with electro-tactile discrimination ability (Allison et al., 2020), and that the higher density of fungiform papillae tends to exist at the tip of the tongue (Shahbake et al., 2005). The results of the present study also show the tip to possess a greater sensitivity, but this time, in response to speeded information rather than acuity. The tip of the tongue may be comparable to the visual fovea of the retina (Haggard & de Boer, 2014), with a greater processing power assigned to the area with the highest fungiform papillae density. To our knowledge, only fungiform papillae density has been explored in response to, specifically, an electrotactile substitution device; however, the tongue possesses a number of other crucial receptors for detecting tactile information. Of particular note are the tongue's mechanoreceptors; Merkel cells, Ruffini endings, and Meissner corpuscles, which provide different qualities of tactile sensation (Capra, 1995; Trulsson & Essick, 2010; Trulsson & Johansson, 2002). A comprehensive review of oral somatosensory awareness suggests that the tongue's morphology of tactile receptors means that light-touch vibrotactile stimulation may provoke the most vivid oral perceptions (Haggard & de Boer, 2014), which consequently is the type of stimuli provided by electrotactile tongue interfaces, such as the BrainPort. Pamir et al. (2020) identified the back of the tongue as an 'informational bottleneck', and when electro-tactile stimulation occurs at the back, there is a reduced comprehension. Again, our results would seem to confirm this idea when cues and targets are unimodal. However, when cues were provided crossmodally through audition, target identification at the back of the tongue seems to improve. We posit that the back of the tongue does represent an informational bottleneck, but conversely, that the reduction of comprehension at this site, can be enhanced by providing redundant spatial information via other modalities. To further this explanation, past research has demonstrated both audio-haptic links for object size estimation (Petrini et al., 2014), and that tactile feedback supports speech production and comprehension (Ito & Ostry, 2012; Sato, Cavé, et al., 2010). Although our results seem to suggest a facilitatory effect of crossmodal cueing for processing tactile information at the back of the tongue, future research should try to examine why this is the case, by for example, using different types of auditory cues. Speech cues are an example of endogenous cueing, requiring top-down processes to understand the vocalisation as symbolically meaningful (Posner, 1980). Considering the role the tongue plays in speech production (Hiiemae & Palmer, 2003; Mermelstein, 1973), tactile attention on its surface may be more easily directed via more natural cueing information (i.e., endogenous speech cues). Endogenous and exogenous cues may use different neural mechanisms to orientate spatial attention (Funes et al., 2007; Hopfinger & West, 2006; Meyer et al., 2018); perhaps the former is more suitable on the tongue, especially as tactile feedback in speech is a far more common occurrence for humans.

We expected that participants who took part in the *reversed mapping* condition to perform better than those in the *standard mapping* condition. That is, matching the position between the keyboard responses and the position on the tongue where the target was displayed (*reversed mapping*) would improve response time and accuracy than matching the position between the keyboard responses to the screen on which the information was provided (*standard mapping*); the reversed mapping condition essentially inverted the configuration of the BrainPort, to make ‘up’ correspond to the tip of the tongue. We did not find, however, a significant difference between *reverse mapping* and *standard mapping* in either reaction time or accuracy; although, there was greater variation in the *standard mapping* condition for both accuracy and reaction time. In a previous study, we found that participants tended to perceive upward arrows as pointing towards the tip of the tongue, when given 10 seconds to explore the BrainPort’s tongue display (Richardson et al., 2020), but, caveated by individual differences in this mapping, such as personality traits. Given this, in the present study we hypothesised that individuals would trend towards identifying information presented to the tip of the tongue as corresponding to the top of the keyboard, and information appearing at the back of the tongue would correspond to the bottom of the keyboard; both stimulus and response paired together across the sagittal plane. However, we found no strong evidence for such a pairing. It may be the case that, in addition to individual differences in the attribution of spatial information to the surface of the tongue (Richardson et al., 2020), there may also be task dependent differences. On the one hand, the spatial manipulation of the vertical plane that is required for perception through the tongue, may be more impactful for tasks that require image exploration and comprehension. On the other hand, tasks such as non-spatially predictive cueing paradigms (used in the present study), are less dependent on how spatial information is presented through the vertical plane. Conversely, Gori et al. (2021) recently suggested that visual calibration may be required for auditory localisation in the vertical plane, perhaps this is also the case for tactile localisation through the 'vertical' plane on the tongue via sensory substitution. More research is certainly required to further understand the spatial interactions of the tongue as an interface method, due to the high variability in reported task performance, both in the present study and also in previous studies with tongue interfaces (Allison et al., 2020; Lee et al., 2014; Nau et al., 2013; Pamir, Canoluk, et al., 2020).

These results, while offering a useful insight into tactile attention and the information processing ability of the tongue, also may have some applied functionality for designer considerations of tongue interfaces. Tongue interfaces are arguably becoming more available and user-friendly with the development of devices, such as the Smart Mouthware Mouse (Saipan LLC, CO, USA), a computer interaction method, that allows a user to use their tongue movements to control a cursor on a screen. Currently, the majority of other devices that facilitate computer interaction, without the use of the hands, rely on eye movements, eye trackers, and facial expression trackers (Chin & Barreto, 2006; Šumak et al., 2019; Surakka et al., 2004). The tongue may offer another avenue by which to interface with machines, but with some critical considerations for effective implementation. The present study identifies areas that researchers and device designers should devote future efforts towards. Of noteworthiness, information provided to the tip of the tongue will likely be more accurately perceived than when presented towards the back, and that it may be more practical to use the tongue in coordination with other remaining modalities, such as audition (Lloyd-Esenkaya et al., 2020).

Although using the BrainPort provided a useful tactile display for the tongue, it may also present some limitations. We initially wanted to compare our results for the tongue to those of Spence and McGlone (2001) for the fingertip. However, as we did not also test the fingertips, as in Spence and McGlone's (2001) study, any comparisons between the two body parts are tenuous. To compare between the fingers and the tongue more directly, an experimental setup would need to be developed to stimulate the finger and thumb with electrotactile feedback, as well as the tongue, with comparable levels of stimulation. This poses an issue as the tongue is ideal for electrotactile stimulation, but the skin on the hands is not. This is due to differences in epithelial composition (Chen et al., 2010), and the saliva on the tongue improving connectivity for electrotactile stimulation (Kaczmarek, 2011). However, finding a way to use the same form of stimulation on the tongue and the hands would indeed be an ideal area for future research. Furthermore, as the device is a stand-alone unit, it was not possible for us to record the actual framerate. Two previous studies have argued that the usable refresh rate of the prior iteration of the BrainPort (the V100) has only been around 5Hz (Lee et al., 2014; Nau et al., 2013), which would have a severe impact on the rapid presentation required for cueing investigations. However, the BrainPort Vision Pro (used here) is an updated version of the device, and the results of the present study would suggest that 40 ms bursts of stimulation were detectable as responses were better than chance; so it would appear that the BrainPort Vision Pro does not succumb to the same ceiling of refresh rate as the V100. Another limitation can be found in our between-group comparison, in that it may have lacked sufficient participants to offer conclusive results given the possibility that our participants could differ in their response to the BrainPort as well as in other characteristics. While we did initially base our recruitment goals on past work, we would recommend that future studies that aim to compare between-groups recruit a larger sample, as this also would allow an examination of individual differences. Additionally, some of the participants mentioned to the researcher that the cue covering the sides of the tongue sometimes masked the following target. That the 'tingling' sensation caused by the electro-feedback remained in the location of the cue, or redirected attention even after the cue had passed. This may also explain the lack of cueing effect in the unimodal tactile condition. Past research has stated that the tongue is ideal for tactile interfacing due to its sensitivity to pressure and electrical stimulation (Grant et al., 2018; Nau et al., 2013; Simaeys et al., 2016). However, the nature of the electrical feedback may not suit everyone, and, in some cases, researchers have noted the attrition rates while using the BrainPort, as a biofeedback method, due to intolerance of the device in the mouth (Badke et al., 2011). As such, we decided to allow the participants to request changes in the intensity of stimulation (starting at 60% and moving up or down until the stimulation was vivid yet comfortable), which is consistent with prior work (e.g., Nau et al., 2013), yet presents a limitation to the results. Future research would perhaps be well directed at exploring how intensity of stimulation influences the salience of the device, and how subjective experience while using the device impacts performance. The tongue is a notoriously difficult object to study, hence the reported respective lack of research (Haggard & de Boer, 2014; Sakamoto et al., 2010), particularly on the tactile capabilities of the tongue. As Frank Geldard wrote in, arguably, the seminal paper that inspired the birth of the field of modern sensory substitution, 'It would be possible to tap out Morse (code) with spaced suffusions of salt on the tongue', but that, 'The chemical senses… are so pedestrian as to not be serious contenders in the world of communication' (Geldard, 1957, pp. 115-116). Electro-biofeedback is likely still the best suited method for exploring orientation of attention on the tongue with currently available technology, as machinery capable of delivering rapid and targeted tactile stimulation (e.g., vibrotactile motors) are too large to fit in the mouth, and classic methods such as touching nylon filaments to the tongue are too slow (Henkin & Banks, 1973). Compressed air presented to the tongue via thin localised tubes could perhaps offer a suitable method to bypass the potential of masking due to 'tingling' in the mouth. This could also present an opportunity to comparably test the fingertips with the tongue using uniform stimulation. With continued progress in technology, both of tongue interfaces and smaller and more precise haptics, hopefully new, more tolerable methods will become available to better understand the tactile capacities of the tongue.

Conclusion

The present analysis examined whether current models of tactile, and crossmodal, attention could be further explored through the tongue. We used a variation of a cueing task previously used to examine tactile and crossmodal attention with other body parts, such as the hands, and delivered the tactile stimulation to the tongue via a vision-to-tactile device (the BrainPort). We specifically examined the factors of cueing (ipsilateral versus contralateral), cueing modality, stimulus-response button mapping, and the sensitivity of different quadrants of the tongue. The results indicated that providing both cue and stimulus information, through tactile means on the tongue, was not as effective as providing cueing information via the auditory modality and stimulus information through the tactile modality. This was an unexpected result, and different to established findings with the hands. Since exogenous attention may use a general mechanism (Spence et al., 2000), we suggest that either the specific anatomy of the tongue (its orientation and location in the body, and without any visual calibration during development), or the nature of the electro-biofeedback used by the BrainPort, impinge on the unimodal tactile capacities on the surface of the tongue. We also found that the tongue's sensitivity gradience from front to back may affect cued attention, but crucially, that this has less of an impact in response to crossmodal auditory cues; a key practical consideration for interface designers in the future.

Context

The tongue is a highly complex sensory organ, and tactile perception on the surface of the tongue is comparatively understudied compared to other body parts. Cueing paradigms have heavily contributed to current models of attentional deployment in humans. These models have been well replicated throughout each spatialised sensory modality, with similar results unimodally and crossmodally (spatial attention in one sense influences another). We used such a cueing paradigm, through a tongue interface, to examine whether the surface of the tongue possessed similar reflexive attentional capacity as the hands, as demonstrated by a previous study from Spence and McGlone (2001). We found that the often-cited general mechanism of spatial attention may not fully apply to the tongue, perhaps due to either its anatomy, or the nature of electro-biofeedback, but note that further experimentation is certainly required as the tactile capacities of the tongue remain elusive. We initially sought to conduct a third experiment, to examine how tactile attention on the surface of the tongue was influenced by crossmodal visual cues, however, the Covid-19 pandemic prevented data collection.

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Chapter 2: Supplementary Material

Stimuli Details

Target stimuli and the tactile image cues (see Figure 4) were created in Microsoft PowerPoint (Version 16.37, 2020), the audio cues were created in Audacity (Version 2.3.2) by generating a stereo sine tone at 440 Hz, 0.8 amplitude for 40 ms duration, that was then split between left-only and right-only audio outputs and then exported as a *.wav* file. Tactile cue and target stimuli were in fact visual information displayed on a computer screen, which were than translated by the BrainPort (positioned in front of the screen) into tactile information delivered to the tongue. Participants, however, were blindfolded and could not see the visual information, and thus we call this information 'tactile' as it would have only appeared as such to the participant. The laptop on which the experiment was run was mirrored via a HDMI cable to a second monitor (2009Wt, Dell, USA) which was positioned in front of the BrainPort. The BrainPort and the screen were covered by a cardboard box to stop the lights in the room from reflecting off the screen and adding uninformative distracting information to the image via the BrainPort.

Data Analysis Code

The following code is written in the R language and was compiled using the RStudio software (Version 1.4.1103). The data-containing .csv files were collated from the *alldata.xlsx* file manually, using the pivot table function inside Microsoft Excel (Version 16.37). The data files can be found at: https://osf.io/qhbk7/?view_only=7238eb229417486faa3de6ad7c6e4a33

```
#Set the working directory
setwd("    ") #add in working directory

#Load in libraries
library(dplyr)
library(ggpubr)
library(ggplot2)
library(ez)
library(rstatix)

#create variables for each experiment for the accuracy data
#this data set has the incorrect and outlying trials removed.
```

```
tdf.error = read.csv("tactile_RM.csv", header = TRUE)
adf.error = read.csv("audio_RM.csv", header = TRUE)
gdf.error = read.csv("group_data.csv", header = TRUE)

#create variables for each experiment for the reaction time data
#this data set has incorrectly answered trials
tdf.RT = read.csv("tactile_RT_data.csv", header = TRUE)
adf.RT = read.csv("audio_RT_data.csv", header = TRUE)
gdf.RT = read.csv("group_RT_data.csv", header = TRUE)

#create factors for SOA factor, as R reads it as numerical data
tdf.error$SOA <- factor(tdf.error$SOA, levels = c(200, 300, 400), labels =
c("200ms", "300ms", "400ms"))
adf.error$SOA <- factor(adf.error$SOA, levels = c(200, 300, 400), labels =
c("200ms", "300ms", "400ms"))
tdf.RT$SOA <- factor(tdf.RT$SOA, levels = c(200, 300, 400), labels =
c("200ms", "300ms", "400ms"))
adf.RT$SOA <- factor(adf.RT$SOA, levels = c(200, 300, 400), labels =
c("200ms", "300ms", "400ms"))

#Warning from R about missing data in tactile set. Checked with ezDesign,
#which found too few trials were were correctly answered, leading to
#unbalanced design with some subjects having no data for some variables.
#These subjects were subsquently removed from the data set
tactile_check <- ezDesign(tdf.RT, SOA, cueing, row = target)

subject_count = as.data.frame(table(tdf.RT$subject))
subject_count[subject_count$Freq<24,]
tdf.RT =
tdf.RT[!(tdf.RT$subject%in%subject_count$Var1[subject_count$Freq<24]),]

#create qq plots.
qqplot.tactile_RT <- ggqqplot(tdf.RT$RT)
qqplot.tactile_error <- ggqqplot(tdf.error$error)
qqplot.audio_RT <- ggqqplot(adf.RT$RT)
qqplot.audio_error <- ggqqplot(adf.error$error)
qqplot.group_RT <- ggqqplot(gdf.RT$RT)
qqplot.group_error <- ggqqplot(gdf.error$error)
```

```
#build anova models
tactile_model_RT <- ezANOVA(data = tdf.RT, dv = .(RT), wid = . (subject),
within = .(SOA, cueing, target))
tactile_model_error <- ezANOVA(data = tdf.error, dv = .(error), wid = .
(subject), within = .(SOA, cueing, target))

audio_model_RT <- ezANOVA(data = adf.RT, dv = .(RT), wid = . (subject),
within = .(SOA, cueing, target))
audio_model_error <- ezANOVA(data = adf.error, dv = .(error), wid = .
(subject), within = .(SOA, cueing, target))

group_model_RT <-  ezANOVA(data = gdf.RT, dv = .(RT), wid = . (subject),
between = .(modality, keymapping))
group_model_error <-  ezANOVA(data = gdf.error, dv = .(error), wid = .
(subject), between = .(modality, keymapping))

#calcuate mean and SD for effect sizes.
tdf.grouped.RT <- group_by(tdf.RT, target)
tdf.means.RT <- summarise(tdf.grouped.RT, mean=mean(RT), sd=sd(SD), n=n())
tdf.grouped.error <- group_by(tdf.error, target)
tdf.means.error <- summarise(tdf.grouped.error, mean=mean(error),
sd=sd(SD), n=n())

adf.grouped.RT <- group_by(adf.RT, target)
adf.means.RT <- summarise(adf.grouped.RT, mean=mean(RT), sd=sd(SD), n=n())

adf.grouped.error <- group_by(tdf.error, target)
adf.means.error <- summarise(tdf.grouped.error, mean=mean(error),
sd=sd(SD), n=n())

#Follow up tests
tactile.RT.target <- pairwise.t.test(tdf.RT$RT, tdf.RT$target, paired =
TRUE, p.adjust.method = "bonferroni")
tactile.error.target <- pairwise.t.test(tdf$error, tdf$target, paired =
TRUE, p.adjust.method = "bonferroni")
audio.RT.SOA <- pairwise.t.test(adf.RT$RT, adf.RT$SOA, paired = TRUE,
p.adjust.method = "bonferroni")
```

```
audio.RT.target <- pairwise.t.test(adf.RT$RT, adf.RT$target, paired = TRUE,
p.adjust.method = "bonferroni")
audio.RT.interaction <- pairwise.t.test(adf.RT$RT, adf.RT$group, paired =
TRUE, p.adjust.method = "bonferroni")
audaudio.error.cueing <- pairwise.t.test(adf$error, adf$cueing, paired =
TRUE, p.adjust.method = "bonferroni")
group.error.modality <- pairwise.t.test(gdf$error, gdf$cueing, paired =
TRUE, p.adjust.method = "bonferroni")



#plots mk2
#Define custom color palette and prepare the data
my4cols <- c("#B80A34", "#CFAD41", "#3F028C", "#57838A")

# 1. Create a box plot for audio RT
adf.RT.p <- ggplot(adf.RT, aes(x = SOA, y = RT, color = target))
adf.RT.bxp <- adf.RT.p + geom_boxplot(aes(color = target)) +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols)

#Create a dot plot for audio RT
adf.RT.dp <- adf.RT.p + geom_dotplot(aes(color = target, fill = target),
                       binaxis='y', stackdir='center', dotsize = 0.7,
                       position = "dodge") +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols) +
  scale_fill_manual(values = my4cols)

#Create boxplot for Audio error
adf.error.p <- ggplot(adf.error, aes(x = SOA, y = error, color = target))
adf.error.bxp <- adf.error.p + geom_boxplot(aes(color = target)) +
  ylab("prop.") +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols)

#Create a dot plot for audio error
adf.error.dp <- adf.error.p + geom_dotplot(aes(color = target, fill =
target),
```

```
                                     binaxis='y', stackdir='center',
                                     dotsize = 0.7, position = "dodge") +
  ylab("prop.") +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols) +
  scale_fill_manual(values = my4cols)

#Generate 2 in one figure
audio.figure <- ggarrange(adf.RT.bxp, adf.error.bxp, labels = c("A", "B"),
                    ncol = 1, nrow = 2)

# 1. Create a box plot for tactile RT
tdf.RT.p <- ggplot(adf.RT, aes(x = SOA, y = RT, color = target))
tdf.RT.bxp <- tdf.RT.p + geom_boxplot(aes(color = target)) +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols)

#Create a dot plot for tactile RT
tdf.RT.dp <- tdf.RT.p + geom_dotplot(aes(color = target, fill = target),
                                     binaxis='y', stackdir='center',
                                     dotsize = 0.7, position = "dodge") +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols) +
  scale_fill_manual(values = my4cols)

#Create boxplot for tactile error
tdf.error.p <- ggplot(tdf.error, aes(x = SOA, y = error, color = target))
tdf.error.bxp <- tdf.error.p + geom_boxplot(aes(color = target)) +
  ylab("prop.") +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols)

#Create a dot plot for tactile error
tdf.error.dp  <-  tdf.error.p  +  geom_dotplot(aes(color  =  target,  fill  =
target),
                                           binaxis='y',
stackdir='center',
```

```
                                          dotsize  =  0.7,  position  =
"dodge") +
  ylab("prop.") +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols) +
  scale_fill_manual(values = my4cols)

#Generate 2 in one figure
tactile.figure  <-  ggarrange(tdf.RT.bxp,  tdf.error.bxp,  labels  =  c("A",
"B"),
                          ncol = 1, nrow = 2)

# 1. Create a box plot for group RT
gdf.RT.p <- ggplot(gdf.RT, aes(x = keymapping, y = RT, color = modality))
gdf.RT.bxp <- gdf.RT.p + geom_boxplot(aes(color = modality)) +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols)

#Create a dot plot for group RT
gdf.RT.dp  <-  gdf.RT.p  +  geom_dotplot(aes(color  =  modality,  fill  =
modality),
                                     binaxis='y', stackdir='center',
                                     dotsize = 0.9, position = "dodge") +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols) +
  scale_fill_manual(values = my4cols)

#Create boxplot for group error
gdf.error.p <- ggplot(gdf.error, aes(x = keymapping, y = error, color =
modality))
gdf.error.bxp <- gdf.error.p + geom_boxplot(aes(color = modality)) +
  ylab("prop.") +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols)

#Create a dot plot for group error
gdf.error.dp <- gdf.error.p + geom_dotplot(aes(color = modality, fill =
modality),
```

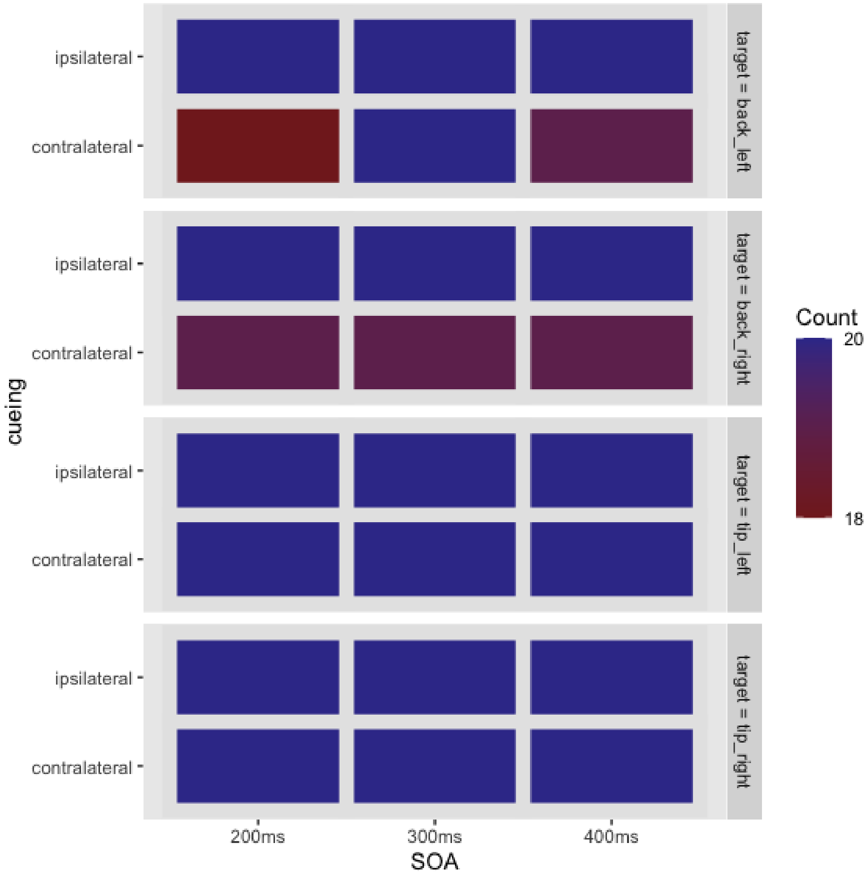
```
                                            binaxis='y',
stackdir='center',
                                            dotsize  =  0.9,  position  =
"dodge") +
  ylab("prop.") +
  theme(legend.position = "bottom") +
  scale_color_manual(values = my4cols) +
  scale_fill_manual(values = my4cols)

#Generate 2 in one figure
group.figure <- ggarrange(gdf.RT.bxp, gdf.error.bxp, labels = c("A", "B"),
                            ncol = 1, nrow = 2)
```

Data Analysis Assumptions

Four participants had to be removed solely from the tactile reaction time experiment analysis, as they failed to answer any trials correctly for certain combinations of factors (specifically when the cue was contralateral and target appeared at the back on the tongue, see Figure S1).

Figure S1

Output from the ezDesign package

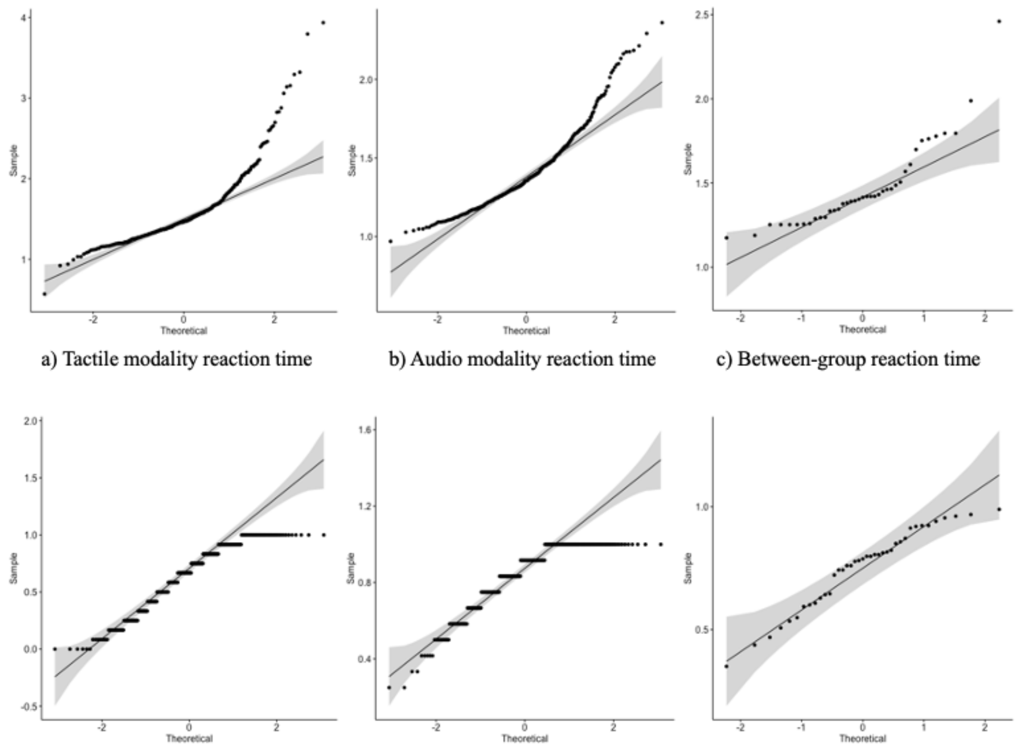


Note. A heat map demonstrating the count of each factor in the tactile modality group for the reaction time analysis. Lower counts indicate missing data due to some participants failing to respond correctly to any trials for that combination of factors. The map demonstrates that when cues were presented to the opposite lateral side (contralateral) of the tongue and the target presented at the back of the tongue, some participants failed to respond correctly to any of the 12 possible trials for that combination of factors

We checked the distribution using normal Q-Q plots (see Figure S2). The data were evaluated as not normally distributed; however, ANOVAs are commonly used even in cases of non-normal distributions as they tend to be robust to this particular violation (Schmider, Ziegler, Danay, Beyer, & Bühner, 2010). The repeated measures ANOVAs were checked for sphericity using Mauchly's test, and the two-way between group ANOVAs were checked for homogeneity of variance with the Levene's test, as this tends to be robust against deviations of normality (Gastwirth, Gel, & Miao, 2009). For the tactile modality reaction time results, Mauchly's test suggested that the factor of SOA was not spherical (W = .61, p = .003), nor was the factor of target location (W = .42, p = .004.), spatial cueing was satisfised automatically as it only contained two levels. The interaction between SOA and spatial cueing was spherical ($W = .83$, $p = .264$), as was the interaction between spatial cueing and target location ($W = .54$, $p = .135$). However, the interaction between SOA and target location ($W = .01$, $p < .001$); and, the interaction between SOA, spatial cueing, and target location ($W = .03$, $p < .001$) did not demonstrate sphericity. For the tactile modality error results, only the factor of target location was found to deviate from sphericity ($W = .36$, $p = .003$). SOA was spherical ($W = .95$, $p = .605$), as where the interactions between: SOA and spatial cueing ($W = .95$, $p = .637$); SOA and target location ($W = .38$, $p = .702$); spatial cueing and target location ($W = .67$, $p = .210$; and the three-way interaction between SOA, spatial cueing, and target location ($W = .30$, $p = .447$). For the auditory cueing modality reaction time results, the factors of SOA and target location were both deemed spherical ($W = .97$, $p = .803$; and, $W = .56$, $p = .083$, respectively); as were the interactions between SOA and spatial cueing ($W = .96$, $p = .717$); SOA and target location ($W = .32$, $p = .560$) spatial cueing and target location ($W = .55$, $p = .076$); and the three-way interaction between SOA, spatial cueing, and target location ($W = .~25$, $p = .343$). For the auditory modality error results, the assumptions of sphericity was met for all combinations of each factor: SOA ($W = .89$, $p = .373$); target location ($W = .52$, $p = .056$); the interaction between SOA and spatial cueing ($W = .95$, $p = .620$); between SOA and target location ($W = .43$, $p = .865$); between spatial cueing and target location ($W = .87$, $p = .809$); and the three-way interaction between SOA, spatial cueing, and target location ($W = .15$, $p = .075$). In cases where the assumption of sphericity was violated, the Greenhouse-Geisser correction was applied to the degrees of freedom and p values. For both two-way between group ANOVAs on the reaction time and error results, respectively, the Levene's Tests suggested that the assumption of homogeneity of variance was met in both instances ($F = 2.12$, $p = .115$; and $F = 1.13$, $p = .349$, respectively).

Figure S2

Normal Q-Q plots showing the non-normal distribution for reaction time and proportion of correct responses in the tactile modality, auditory modality and between group designs.



a) Tactile modality reaction time b) Audio modality reaction time c) Between-group reaction time

d) Tactile modality error e) Audio modality error f) Between-group error

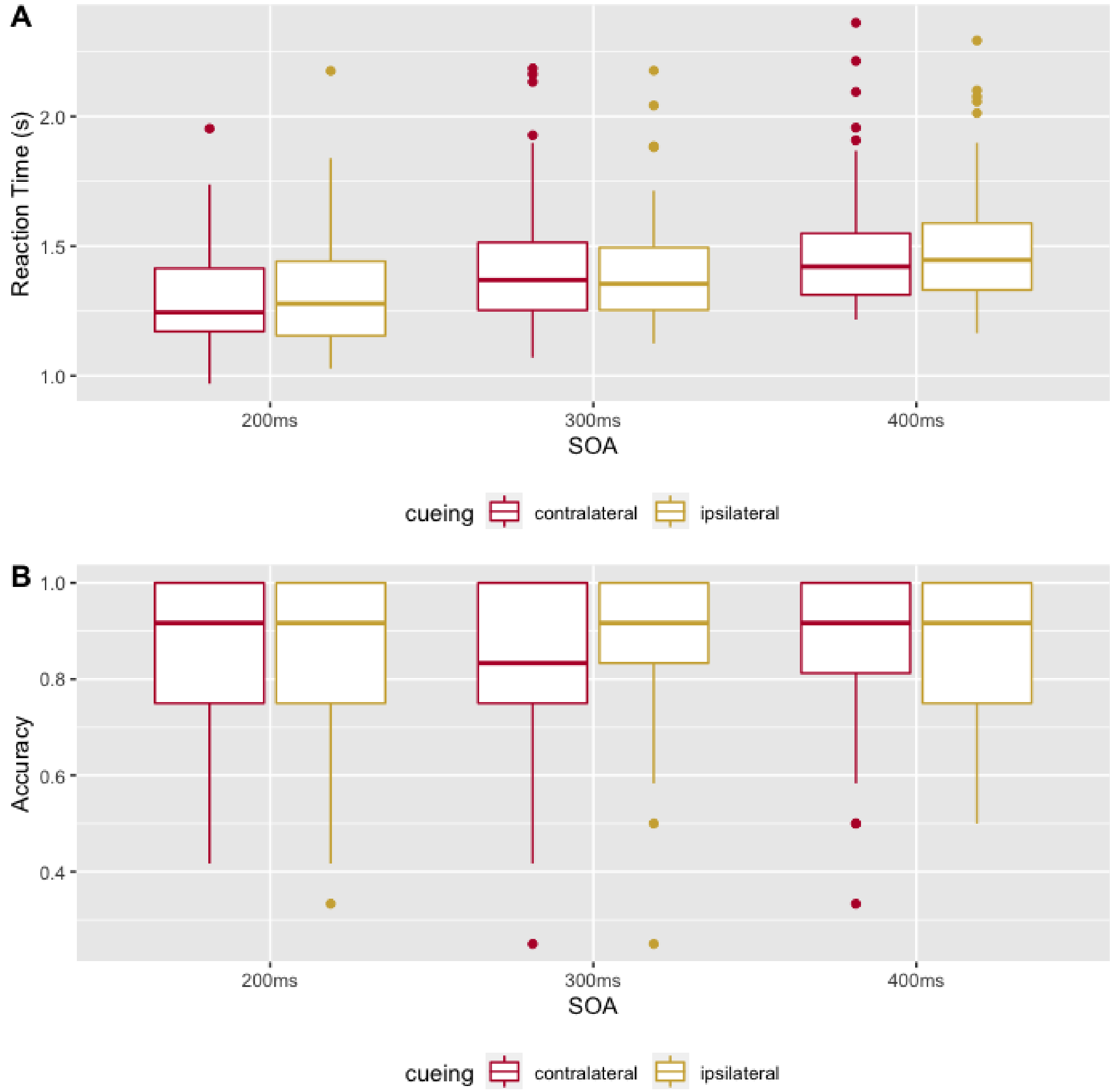
Supplementary Results

The following tables have been included in this supplementary section to maintain brevity in the main text. Table S1 includes reaction times and the percentage of correct answers for each of the within-subject factors in the *tactile* modality experiment. Table S2 includes reactions times and the percentage of correct answers for each of the within-subject factors in the *audio* modality experiment. The purpose of including these tables in the supplementary material was to allow other researchers to more closely examine each factor, whereas, the figures in the main text allow for easier visual comparison of the main trends between factors. Figure S3 demonstrates the small, but significant, effect of cueing on accuracy that was also excluded from the main text as accuracy was not the main focus point of the cueing analysis. We also used mixed ANOVAs to examine whether modality had an interacting effect with cueing. We did not include these analyses in the main text as they duplicate and therefore support the main effects already reported; however, these analyses offer additional interaction results for interest. For reaction time, the mixed ANOVA confirmed no significant effect for modality ($F(1, 38) = 1.46$, $p = .235$, $\eta^2 = .030$), no significant effect for cueing ($F(1, 38) = .69$, $p = .419$, $\eta^2 = .003$), and no significant interaction ($F(1, 38) = 1.25$, $p = .271$, $\eta^2 = .006$). For the accuracy analysis, the mixed ANOVA calculated that audio cues led to significantly more accurate responses than tactile cues ($F(1, 38) = 8.15$, $p = .006$, $\eta^2 = .168$), that ipsilateral cues led to significantly more accurate responses than contralateral cues, but with a very small effect size ($F(1, 38) = 4.17$, $p = .048$, $\eta^2 = .004$), and there was no significant interaction ($F(1, 38) = .07$, $p = .790$, $\eta^2 < .001$).

Similarly, we also conducted mixed ANOVAs to compare the factors of keyboard mapping and target location, for a closer examination of any possible interaction. For the reaction time analysis, we found no significant effect for keyboard mapping ($F(1, 37) = 1.88$, $p = .179$, $\eta^2 = .041$), but like the main text, a significant effect for target location ($F(3, 111) = 12.93$, $p < .001$, $\eta^2 = .039$), and there was no significant interaction between these factors ($F(2, 111) = .27$, $p = .848$, $\eta^2 < .001$). For the accuracy analysis, we found no significant effect for keyboard mapping ($F(1, 38) = 3.47$, $p = .070$, $\eta^2 = .056$), a significant effect for target location ($F(3, 114) = 9.55$, $p < .001$, $\eta^2 = .066$), and no significant interaction ($F(3, 114) = .69$, $p = .558$, $\eta^2 = .005$). Supplementary follow up tests were not conducted as these results are also in the main text.

Figure S3

Supplementary results of the audio cueing modality experiment: plotting stimulus onset asynchrony (SOA) and cueing.



Note. A =boxplots showing individual reaction time mean scores of each participant, lower scores is better; B = boxplots showing individual mean proportion of correct responses (Accuracy) of each participant, higher scores are better. Upper and lower sections of the box correspond to 25th, and 75th percentiles, respectively; top and bottom whiskers correspond to highest and lowest value up to 1.5 times the interquartile range.

Table S1

Mean reaction times (RT) and percentage of correct responses (Corr. %) in the tactile cueing modality group.

Cue	Ipsilateral												Contralateral											
SOA	200 ms				300 ms				400 ms				200 ms				300 ms				400 ms			
Target	TR	TL	BR	BL	TR	TL	BR	BL	TR	TL	BR	BL	TR	TL	BR	BL	TR	TL	BR	BL	TR	TL	BR	BL
RT (s)	1.53	1.47	1.60	1.58	1.47	1.48	1.55	1.70	1.49	1.46	1.62	1.67	1.50	1.37	1.59	1.54	1.41	1.45	1.55	1.63	1.55	1.55	1.66	1.67
SD	2.09	.58	.59	.51	.50	.51	.59	.57	.40	.37	.63	.59	1.55	.35	1.36	.65	.41	.41	.43	.52	.45	.39	.44	.47
Corr. %	76.8	81.6	52.1	58.8	73.3	77.5	63.3	53.8	75.0	77.7	62.1	57.1	77.9	78.8	50.8	51.7	70.4	73.3	57.9	53.3	70.4	73.3	56.7	56.7
SD	42.9	38.7	50.0	49.3	44.3	41.8	48.3	50.0	43.4	42.4	48.6	49.6	41.6	41.0	50.1	50.1	45.7	44.3	49.5	50.0	45.7	44.3	49.7	49.7

Note: SOA = Stimulus onset asynchronies; TR = tip right target location; TL = tip left target location; BR = back right target location; BL = back left target location. SD = standard deviation.

Table S2

Mean reaction times (RT) and percentage of correct responses (Corr. %) in the auditory cueing modality group.

Cue	Ipsilateral												Contralateral											
SOA	200 ms				300 ms				400 ms				200 ms				300 ms				400 ms			
Target	TR	TL	BR	BL	TR	TL	BR	BL	TR	TL	BR	BL	TR	TL	BR	BL	TR	TL	BR	BL	TR	TL	BR	BL
RT (s)	1.27	1.29	1.39	1.32	1.31	1.36	1.41	1.49	1.49	1.42	1.50	1.51	1.22	1.26	1.38	1.35	1.34	1.39	1.41	1.47	1.45	1.43	1.46	1.50
SD	.49	.46	.63	.29	.27	.51	.40	.59	.77	.37	.49	.42	.30	.34	.47	.37	.35	.52	.38	.54	.46	.32	.30	.43
Corr. %	82.1	84.2	79.6	76.7	85.5	87.1	82.1	82.5	84.6	86.7	79.6	81.3	81.3	84.6	79.2	77.5	78.8	82.1	77.9	77.5	83.3	83.8	78.8	80.8
SD	37.7	36.6	40.4	42.4	34.9	33.6	38.4	38.1	36.2	34.1	40.4	39.1	39.2	36.1	40.7	41.8	41.0	38.4	41.6	41.8	37.3	37.0	41.0	39.4

Note: SOA = Stimulus onset asynchronies; TR = tip right target location; TL = tip left target location; BR = back right target location; BL = back left target location. SD = standard deviation

Supplementary References

Gastwirth, J. L., Gel, Y. R., & Miao, W. (2009). The impact of Levene's test of equality of variances on statistical theory and practice. *Statistical Science,* 343-360. https://www.jstor.org/stable/25681315

Schmider, E., Ziegler, M., Danay, E., Beyer, L., & Bühner, M. (2010). Is it Really Robust? Reinvestigating the Robustness of ANOVA against Violations of the Normal Distribution Assumption. Methodology, 6(4), 147-151. doi:10.1027/1614-2241/a000016

Introduction to Chapter 3

In Chapter 2, *Orientation of Tactile Attention on the Surface of the Tongue*, we demonstrated that current theories surrounding tactile attention may not be easily translatable to the surface of the tongue. As response accuracy was generally low at the back of the tongue, it is crucial that SSDs relying on tongue displays provide the most vital information at the tip of the tongue, as this is the location that offers the most vivid perceptual ability. Interestingly, replacing unimodal tactile cues with crossmodal auditory cues seemed to improve attentional capacity. Again, this may have implications in a sport and exercise setting. Perhaps reducing the amount of information presented to the tongue, by offloading some perceptual load to other modalities, may help improve the efficacy of identifying visual features quickly.

The combined results of Chapter 1 and Chapter 2 may help to inform some rough principles that should be considered when using a tongue interface for exercise. Adaptive and customisable devices are a necessity for two reasons. Firstly, that perceptual ability is far superior at the tip of the tongue compared to the back, so the most important visual features should be prioritised. However, this is mediated by the second point. The adopted perspective when using a tongue interface is flexible and affected by individual and task specific differences; meaning, that attributing spatial information to the tongue will not be uniform.

Chapter 3 moves on from applying psychophysical experiments to the tongue, and instead explores the barriers to exercise participation for people with blindness and visual impairments. Initially, the purpose of the study was to examine the general activity levels for people with visual impairments, identify barriers to participation, and then explore potential areas for technological interventions. However, part way through data collection for the study, the Coronavirus-19 pandemic hit the UK, and a stay-at-home order was enforced. For this reason, we felt like we could not continue data collection on a topic that inquired about typical exercise habits, since habits were severely disrupted by the stay-at-home order. Instead, we changed the scope of the study to factor in the impact of the Coronavirus-19 lockdown on exercise for people with visual impairments. A significant aspect of the study that changed was the focus on finding areas for technological intervention, because the pandemic instead offered the opportunity to explore what technology people with visual impairments started using to help them exercise during the pandemic. Instead of enquiring about hypothetical use cases of technology, we could ask about the technology that people with visual impairments actually began to use due to the disruption of exercise habits.

Chapter 3 Statement of Authorship

This declaration concerns the article entitled:									
Access to exercise for people with visual impairments during the Coronavirus-19 pandemic									
Publication status (tick one)									
Draft manuscript		**Submitted**		**In review**		**Accepted**		**Published**	x
Publication details (reference)	Richardson, M., Petrini, K., & Proulx, M. J. (2022). Access to exercise for people with visual impairments during the Coronavirus-19 pandemic. British Journal of Visual Impairment. https://doi.org/10.1177/02646196211067356								
Copyright status (tick the appropriate statement)									
I hold the copyright for this material			Copyright is retained by the publisher, but I have been given permission to replicate the material here		x				
Candidate's contribution to the paper (provide details, and also indicate as a percentage)	The candidate contributed to / considerably contributed to / predominantly executed the… Formulation of ideas: 90% Design of methodology: 95% Experimental work: 100% Presentation of data in journal format: 85%								
Statement from Candidate	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.								
Signed	[redacted]			**Date**	10/01/2022				

Chapter 3: Access to Exercise for People with Visual Impairments During the Coronavirus-19 Pandemic

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We have no known conflict of interest to disclose.

Data can be requested at: https://osf.io/5f9zq/?view_only=cf9ab8ed93b54e8cbb2f4a35668c5b16

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Abstract

People with blindness and visual impairments have reduced access to exercise compared to the general population during typical societal functioning. The Coronavirus-19 pandemic completely disrupted daily life for most individuals worldwide, and in the UK a stay-at-home order was enforced. One of the sole reasons an individual could leave their home was for the purpose of daily exercise. Here, we examined how the UK national lockdown impacted access to exercise for people with blindness and visual impairment. We used a mixed methods design, collecting quantitative data from two established measures (the Exercise Barriers and Benefits Scale, and the International Physical Activity Questionnaire), and qualitative data from open-ended questions. We found that during the initial stages of the lockdown perceived barriers to exercise increased compared to pre-pandemic levels, driven by factors such as the closure of exercise facilities and additional difficulties posed by social distancing. Interestingly, during the later stages of the UK Coronavirus-19 response, perceived barriers decreased to lower than pre-pandemic levels. Thematic analysis indicated that this may have been due to participants finding new online methods to exercise at home, in combination with the tentative reopening of facilities.

Keywords: exercise participation, exercise barriers, coronavirus-19, blindness, partially sighted

Introduction

Exercise is one of the most critical activities that humans can perform for their health and wellbeing. It is well documented that exercise is not only beneficial for physical health (Cotman & Berchtold, 2002; Ito, 2019; Ness et al., 2007), but it also has a vast number of psychological and social benefits (Penedo & Dahn, 2005; Raglin, 1990; Ruby et al., 2011). While many individuals struggle to exercise due to a variety of time, financial, and motivational reasons (Ebben & Brudzynski, 2008; Tappe et al., 1989), people with blindness and visual impairments have added barriers to exercise on top of those faced by the general population (Capella-McDonnall, 2007; Matoso & Portela, 2020). Prior research into exercise participation for populations with blindness and visual impairments suggest that some exhibit comorbidity with symptoms related to insufficient exercise, such as hypertension, obesity, and depression (Mann et al., 2014; Shields et al., 2012). Conversely, for groups with blindness and visual impairments, research has documented many examples in which exercise and sports can have positive effects. For example, in older adults with visual impairments, dance programmes have shown to improve aspects such as mobility, balance, and cardiovascular fitness, but also increased measures of cognitive flexibility and quality of life (Hackney et al., 2015; Woei-Ni Hwang & Braun, 2015). In fact, the quality of life of national level athletes with visual impairments compared to matched controls was found to be higher in every aspect, including social functioning, perception of health, and physical functioning (Ilhan et al., 2021). Undoubtedly, access to exercise is incredibly important for health and well-being and, with the right support, people with blindness and visual impairments can participate in various forms of sport and exercise under normal circumstances.

However, the Coronavirus-19 pandemic has disrupted daily life for a high number of individuals across the globe and in the UK a national lockdown was implemented on the 23rd of March 2020 under the Coronavirus Act 2020 (*Coronavirus Act 2020*, 2020). Under this act, the population was required to stay in their homes unless shopping for essential food or medicine, requiring medical attention, caring for a vulnerable person, travelling to a place of work (if essential), and finally, for one form of exercise per day. Similar measures were implemented in many other countries (Dunford et al., 2020). Research around the globe suggests that those with disabilities have been among the most severely affected by lockdowns and social distancing (Jalali et al., 2020; Mbazzi et al., 2020; Safta-Zecheria, 2020). The additional difficulties faced by people with visual impairments, include additional transmission risk from navigating by touch and identifying food quality by smell (or closer visual inspection), being unable to change working routines to work from home (Suraweera et al., 2021), and reduced feelings of autonomy and independence (because of having to rely on other family members or online services for groceries). Furthermore, people with blindness and visual impairments reported how sporting hobbies decreased outside, but slightly increased inside the home (Gombas & Csakvari, 2021).

During the early stages of the UK lockdown the government allowed and actively encouraged exercise (*Coronavirus Act 2020*, 2020). People who were typically low exercisers before the lockdown reported an increase in exercise participation during lockdown (Constandt et al., 2020). However, the same study also found that for those above the age of 55 years, people who previously were high exercisers before the pandemic, and people that exercised with others reported a decrease in exercise participation. While the majority of a sampled population in the UK maintained normal levels of exercise during lockdown, groups more at risk for Coronavirus (including those with a disability) were associated with doing less physical activity than they did prior to the pandemic (Rogers et al., 2020). Many people with visual impairments require assistance with exercise, travel to exercise, or specialised coaching (Seham & Yeo, 2015; Skaggs & Hopper, 1996), hence reduced access to this type of assistance dictated by the pandemic restrictions could have impacted access to exercise for those needing support.

This study aimed to understand how access to exercise was impacted by the Coronavirus-19 pandemic, comparing early lockdowns, and later lockdowns to data collected prior to the commencement of the pandemic. Based on the limited evidence on the effects of the Coronavirus-19 restrictions and lockdown on individuals' levels of exercise, we first hypothesised that there would be a difference in participation in, and perception of barriers to, exercise during lockdown compared to before the lockdown. We could not predict the direction of this change in participation and in perception of barriers, as on the one hand, working from home for many participants could have increased available time to exercise. On the other hand, a reduction in open exercise facilities (such as gyms and leisure centres) could have reduced exercise participation and be perceived as a great barrier to exercise (Constandt et al., 2020; Rogers et al., 2020). Our second hypothesis was that those living in less urban areas would have greater exercise participation than those in more urban areas as facilities had closed, and that open spaces and access to countryside may offer more opportunities to exercise with a reduced impact of the lockdown on these areas.

Methods

Participants

We recruited sixty-one people with blindness and visual impairments overall, twenty-one participants took part during the pre-lockdown period (7 females, 11 males, 3 did not answer; mean age in years = 39, range = 17-62 years). Twenty-two participants took part during the early lockdown period (14 females, 10 males; mean age in years = 39, range = 17-70 years), and eighteen participants took part during the late lockdown period (11 females, 6 males, 1 did not answer; mean age in years = 47, range = 18-68 years). See Appendix A for further participant details. All participants provided informed consent and the study was approved by the University of Bath Psychology Research Ethics Committee (ethics number: 19-088). We recruited participants via social media and word of mouth. As the questionnaires were anonymous it is possible that some of the participants may have overlapped between groups.

Materials and Measures

The International Physical Activity Questionnaire (IPAQ) was developed to monitor physical activity to a global standard (Craig et al., 2003), and has since become the most used measure of physical activity in academic literature (Van Poppel et al., 2010). The short version (IPAQ-SF) consists of nine items that cover activity at four different intensities (vigorous intensity; moderate intensity; walking; and sitting, respectively). The typical response format is to provide a seven-day recall of the number of minutes spent doing any of the four activity intensities. For example, 'During the last 7 days, on how many days did you do vigorous physical activities like heavy lifting, digging, aerobics, or fast bicycling?', followed by, 'How much time did you usually spend doing vigorous physical activities on one of those days?'. The IPAQ-SF is typically used to provide an estimate of Metabolic Equivalent of Task (MET), a measure of energy expenditure for a given activity. MET can be robustly calculated by multiplying the relative (to body weight) oxygen consumption of an activity by oxygen consumption while sitting. However, this method of calculating METs requires specialised equipment (such as Douglas Bags or VO_2 gas analysers) and a great deal of time. The IPAQ-SF calculates an estimate of METs using only self-reported time spent exercising at different intensities and is far more feasible for establishing trends remotely, or in large groups of people. To our knowledge the IPAQ-SF has been used, but not validated with people with visual impairments (e.g., Barbosa et al., 2019; López-Sánchez et al., 2019).

The Exercise Benefits/Barriers Scale (EBBS) is a two-part psychometric measure (barriers and benefits), that can be used in isolation of one another (Sechrist et al., 1987). To maintain brevity, only the barriers section of the questionnaire was adopted for the present study. The benefits of exercise are well documented, well reported, and we accept that most members of a Western demographic understand that exercise is beneficial to health and would unnecessarily extend the length of time required without making a commensurate contribution. The barriers section of the EBBS has been successfully applied to several demographics that often have reduced access to exercise including the elderly (Fonseca Victor et al., 2012), and people with mobility impairments (Stroud et al., 2009; Thomson et al., 2016), but to our knowledge, has not been specifically validated for people with visual impairments. We also asked our participants other more flexible open-ended questions to probe both specific aspects of exercise during the pandemic and to understand the presence of exercise support networks under normal circumstances compared to disruption.

Table 1

Open-ended questions presented to participants at the end of the survey.

1.
    a. What sports or exercise do you regularly participate in?
    b. Before the virus, what sports did you regularly participate in?
2. What is your biggest barrier to exercising?
3. How do you currently get around that barrier, or how would you like to get around that barrier?
4. *Would you prefer to exercise with, solely sighted individuals, solely visually impaired individuals, or a mixture of sighted and visually impaired individuals?
5. What, if any, technology has helped you exercise?

6. What has helped you during lockdown to exercise?
7. *Do you have a dream sport that you would like to participate in, but that your impairment currently prohibits?
8. *If you were in charge of designing an exercise video game (like Wii sports), what would the key features be?

Note. *These questions were included for purposes outside those of the present study and thus were not considered further. Question 1a was used in data collection prior to the onset of the pandemic. Question 1b was used after the onset of the pandemic.

Procedure

The survey was hosted on the online platform Qualtrics (Qualtrics, Provo, UT, USA) and was split into four main sections: the first pertained to demographic information (gender, age, level of impairment, onset of impairment, residential location), the second and third sections contained the IPAQ-SF, and EBBS questions respectively, and the fourth section contained the open-ended questions (Table 1). Some of the questions had to be slightly adjusted from the initial pre-lockdown data to make sense, or encapsulate, exercise given the pandemic. For example, the first open-ended question was changed from 'What sports do you regularly participate in?', to, 'Before the virus, what sports did you regularly participate in?'. Another example of a slight wording change was for the introduction to the IPAQ-SF questions, asking the participant to reflect on their exercise specifically 'on an average week during the Coronavirus pandemic', rather than purely an average week. We made these slight wording changes to ensure clarity and specificity of responses; the impact of the lockdown changed the definition of words such as 'typical' and 'average'. Pre-lockdown data was collected between 29th May 2019 to 10th March 2020. Early lockdown data was collected between 4th May 2020 to 1st July 2020. Late lockdown data was collected between 7th July 2020 to 22nd February 2021.

Data Analysis

Data were exported from Qualtrics into *.csv* files and processed in Microsoft Excel. Statistical analysis on the IPAQ-SF and EBBS results was conducted using the Pandas (version 1.2.1) and Pingouin (version 0.3.9) libraries for Python (version 3.8.5).

For the thematic analysis, we followed established practices based on common qualitative methods for psychology (Braun & Clarke, 2006). We used an inductive and deductive approach due to the specificity of the questions (the questions were open, but short and highly targeted) and reflected on the data from a critical realist perspective (generally taking each participant at their word) with aspects of constructionism (but also looking for deeper meaning or metaphor). The coding procedure entailed separating out the qualitative responses from the rest of the questionnaire into a separate Word file. This document was then printed into a hard copy which was read through for immersion in the data, and then parsed a second time, to generate initial codes and notes. Codes were refined, however, no large changes were needed as each participant's response was concise and in answer to a specific question (i.e., as opposed to a longer open interview, in which a participant may make many complex and overlapping points which require untangling). Answers to the question, 'What has helped you to exercise during lockdown?', were not analysed due to too few responses, perhaps due to the similarity to the previous question, 'What, if any, technology has helped you exercise?'.

In the case that a participant responded with 'unsure', the entry was treated as a missing value. One participant responded to the question 'During the last 7 days, how much time did you spend sitting on a weekday?', with 40 hours. Here we assumed that the question had been misunderstood and divided the total hours by 7. In cases where the participant responded to the question 'During the last 7 days, how much time did you usually spend sitting on a weekday?', with a variation of 'the rest of the day', responses were coded as 180 minutes. All outlying entries that recorded more than 180 minutes, were truncated to 180 minutes, as per the IPAQ-SF recommendation (*IPAQ Scoring Protocol - International Physical Activity Questionnaire*, n.d.). A Python function was used to convert the IPAQ-SF results into estimated weekly METs (Boyle et al., 2021)

Results

The assumption of normality was violated for the EBBS pre-lockdown group (*Shapiro-Wilk's* $W = .888$, $p = .020$), but not the early or late lockdown groups (*Shapiro-Wilk's* $W = .970$, $p = .717$; *Shapiro-Wilk's* $W = .935$, $p = .234$, respectively). The data were normally distributed for all residential location groups in the EBBS: a major city (*Shapiro-Wilk's* $W = .922$, $p = .237$); a small city/large town (*Shapiro-Wilk's* $W = .954$, $p = .440$); a town (*Shapiro-Wilk's* $W = .919$, $p = .183$); and a rural area (*Shapiro-Wilk's* $W = .918$, $p = .267$).

For the IPAQ-SF the data deviated significantly from a normal distribution for the pre-lockdown and early lockdown groups (*Shapiro-Wilk's* $W = .653$, $p < .001$; *Shapiro-Wilk's* $W = .847$, $p = .003$, respectively), but not the late lockdown group (*Shapiro-Wilk's* $W = .902$, $p = .062$). All residential location groups in the IPAQ-SF failed to satisfy the assumption of normality: a major city (*Shapiro-Wilk's* $W = .746$, $p = .001$); a small city/large town (*Shapiro-Wilk's* $W = .706$, $p < .001$); a town (*Shapiro-Wilk's* $W = .840$, $p = .013$); and a rural area (*Shapiro-Wilk's* $W = .759$, $p = .003$). The Levene's Test demonstrated that there was homoscedasticity for lockdown stage in both the EBBS ($F(2, 58) = .022$, $p = .978$), and the IPAQ-SF ($F(2, 58) = .619$, $p = .542$), as well as the factor of residential location in both the EBBS ($F(3, 57) = .516$, $p = .673$), and the IPAQ-SF ($F(3, 57) = .892$, $p = .451$). Hence, for the EBBS data analyses we used a between-subject analysis of variance (ANOVA) due to only one group deviating from normality, and because ANOVAs are robust to deviation from a normal distribution (Schmider et al., 2010). For consistency we also used an ANOVA for the IPAQ-SF, but since the deviations from normality were more severe, we also ran a non-parametric model to compare the results.

Two between-subject analyses of variances (ANOVAs) were conducted on the EBBS and the IPAQ-SF scores, respectively (see Table 2 for mean scores and standard deviations). The analysis included two between-subject factors, the lockdown stage (pre-lockdown, early-lockdown, and late-lockdown) and the area of residence (major city, small city/large town, town, and rural area). The results showed that for the EBBS scores there was a significant effect of lockdown stage ($F(2, 49) = 24.50$, $p < .001$, $\eta_p^2 = .50$), but not of residence location ($F(3, 49) = .48$, $p = .696$, $\eta_p^2 = .03$). Also, no significant interaction effect between these factors was found ($F(6, 49) = 2.17$, $p = .062$, $\eta_p^2 = .21$). The results for the MET scores revealed no significant main effect of lockdown stage ($F(2, 49) = .41$, $p = .666$, $\eta_p^2 = .02$), residence location ($F(3, 49) = .79$, $p = .504$, $\eta_p^2 = .05$), or interaction between these factors ($F(6, 49) = 1.64$, $p = .157$, $\eta_p^2 = .17$). A Kruskal-Wallis H test also aligned with the result of the ANOVA, indicating no significant difference in lockdown stage or residential location ($H(2) = .495$, $p = .780$; $H(3) = 1.296$, $p = .730$, respectively). As a significant difference of lockdown stage was found for the EBBS, posthoc corrected-for-multiple-comparisons Games-Howell t-tests were carried out on this factor, as it is more robust against varied group sample sizes and deviations from normality (Toothaker, 1993). Our participants reported that there were significantly more perceived barriers in early-lockdown compared to pre-lockdown ($t(40.2) = 2.47$, $p = .038$, $g = .74$), significantly more perceived barriers early-lockdown compared to late-lockdown ($t(36.3) = 6.27$, $p = .001$, $g = 1.95$), and significantly more perceived barriers pre-lockdown compared to late-lockdown ($t(32.9) = 4.40$, $p = .001$, $g = 1.38$).

Table 2

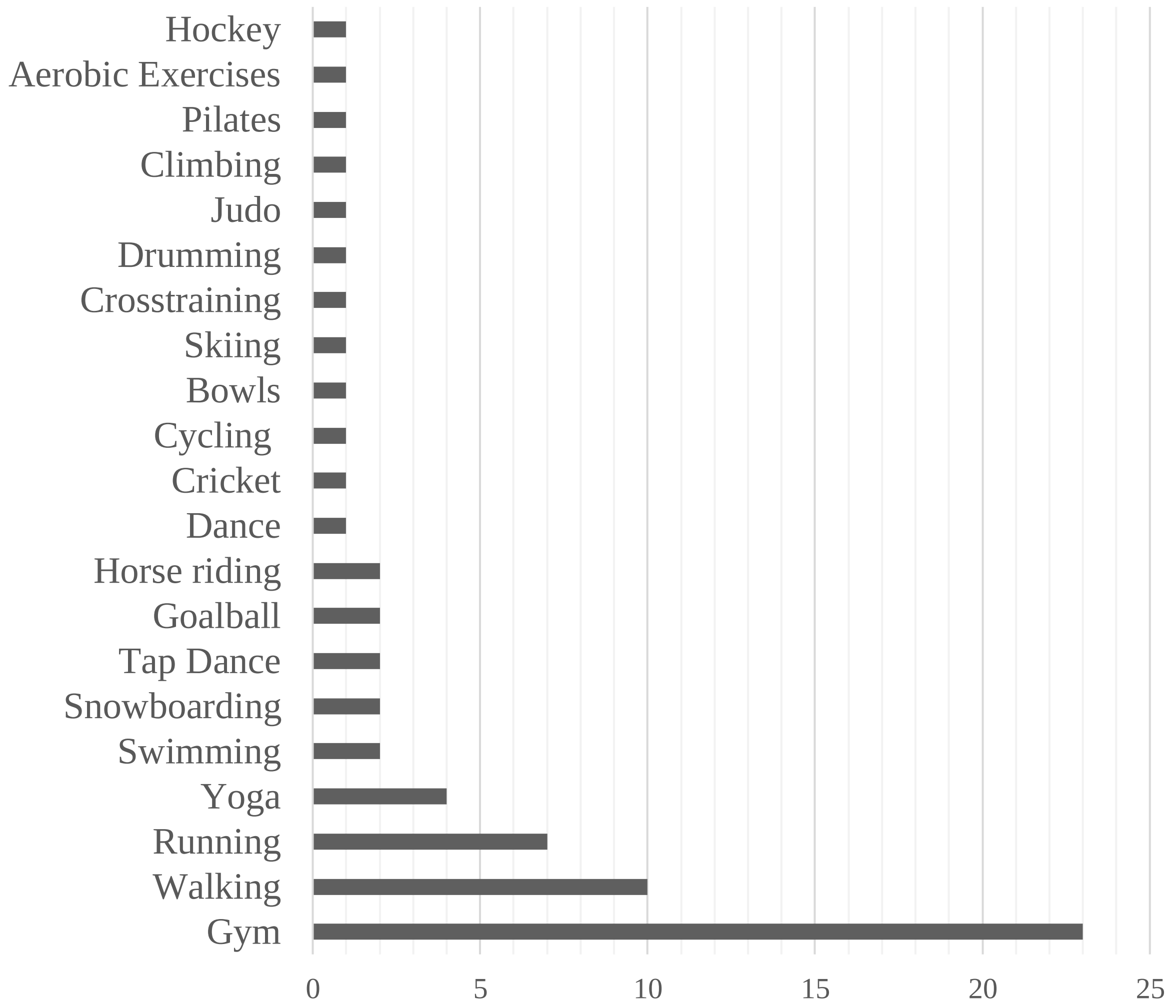
Mean scores and standard deviation for the Exercise Barriers and Benefits Scale (EBBS), and Metabolic Equivalence of Task (MET) as calculated by the International Physical Activity Questionnaire (IPAQ-SF).

	N	**EBBS**	***SD***	**MET**	***SD***
Pre-lockdown	21	41	7	2513	3345
Major city	4	42	7	5392	5958
Small city	5	38	7	3058	3730
Town	6	39	5	1472	1290
Rural Area	6	43	8	1181	553
Early-lockdown	22	46	8	2089	1777
Major city	6	48	5	2093	1745
Small city	8	43	7	1645	1253
Town	5	53	8	3135	2651
Rural Area	2	38	1	1457	1541
Late-lockdown	18	30	8	1929	1574
Major city	4	25	8	1812	1243
Small city	6	33	10	1254	1091
Town	4	31	4	2132	1349
Rural Area	4	30	8	2854	2563

Responses to the questions ‘What sports or exercise do you regularly participate in? / Before the virus, what sports did you regularly participate in?’ were collated into a chart to give an overview of most common sports and variety of sports in which our participants participate in (see Figure 1).

Figure 1

A chart demonstrating the count of sports and exercise activities regularly undertaken by our sample.



Note. Different indoor training sessions (e.g., weights, high intensity training) were simplified into the category 'gym'.

What is the biggest barrier to exercise?

Pre-lockdown

Prior to the pandemic, the most common barriers that were reported by the participants were themed as: lack of specific support, lack of motivation, inaccessible transport, and comorbidity. For one participant, many classes lack specific support for visual impairments:

'Finding people that will support someone with visual impairment. Increasing knowledge for support in class'

This may exemplify that the participant was motivated to join a class, but classes often cannot provide adequate support for members with blindness or visual impairments. Another also echoed a similar sentiment on specific support:

'I am unable to operate gym equipment or see someone who is running a class'

For one individual exercising in a council run gym was not permitted without support:

'gyms run by the council don't let me in without a carer and I don't have one during the week as my husband works'.

This response also hints at the role of family members in supporting exercise accessibility.

Lack of motivation was often reported as the major barrier to exercise participation:

'I cannot be bothered'
'Getting in the mood after a day at work'
'Lack of free time and personal motivation'

Regarding inaccessible transport, one individual commented on the difficulties of transporting a bike to safe routes:

'once I'm on a proper route it's easy for me to follow it but I am not safe to cycle on an ordinary road'.

Another said it's difficult to find local activities, perhaps also alluding to lack of accessible transport:

'trying to find those activities I like to do, that caters for visually impaired people in my area'.

Some participants commented on non-visual impairment related health and well-being issues that prevented them from exercising, which we coded together under the theme of comorbidity. For example, two participants reported specific non-visual impairment related barriers to exercise:

'[I have] an underactive thyroid… [and] chronic pain'
'I have seriously injured my back and this is [a] major influence'.

During Lockdown

During the pandemic the most reported barriers still included aspects of motivation, support, transport, and comorbidity, but more specifically centred around closed facilities (e.g., gyms and sport centres) and shielding/social distancing advice which affected existing support networks. For example:

'Because of my other illness I have to shield'
'social distancing is difficult for some with little or no sight'
'parents are shielding so walking is impossible without a guide'.

Eight participants mentioned about how closed facilities (including gyms, community centres, exercise classes, and swimming pools) have presented barriers to exercise, and one goes further to say:

'exercise classes have gone online and I cannot see my iPad screen well enough to follow a class'.

There were other prominent concerns over difficulties in social distancing as a person with visual impairments, and poor public understanding of visual impairments:

'Walking outdoors makes me feel more anxious now as I wish to stay safe. I do not look blind. I was told a number of times that I look like I am training my guide dog'.

How do/would you overcome this barrier?

Pre-lockdown

Prior to the pandemic, the commonly mentioned methods for overcoming barriers were relying on friends and family for travel or exercise assistance, using gym equipment at work, travelling distances to get to places that can offer suitable support:

'I get around [the barrier] by travelling significant [distances] to cricket practice'
'getting friends to take me where I want to go'
'meeting friends at a time that suits them'

During lockdown

These methods were no longer possible once social distancing was in place, for example, one person commented:

'Usually [I] use public transport but [I'm] avoiding at the moment due to risk'.

Other participants mentioned that walking at home or with members of their households became a prominent method of exercising. Home gym equipment and online classes were also mentioned as ways to navigate the barriers posed by Coronavirus-19 to exercising:

'I purchased an exercise bike, which has helped me keep a level of fitness'

In the later section of the lockdown after some facilities had reopened, a participant reports a method of exercise by:

'Home gym and going to a different [open] swimming pool further away'.

What technology has helped with exercise during Covid-19?

The technology that participants reported to help with exercise was grouped into four categories (or themes). The two most prominent categories reported were themed as social technology and fitness trackers. Social technology included using Facebook, Zoom, YouTube, and Instagram to help increase exercise participation. Fitness trackers included FitBit and smart watches, using health data from smart phones and tablets and step-counters. Other categories included navigation assistance (Google Maps, two-way radio, flashlight, and guide dog), and exercise equipment (treadmill, bike, and exercise bike). Two individuals both attributed the internet generally as a faciliatory technology, and 4 participants (out of all 40 participants that were asked the question) either did not answer, or reported that there was no faciliatory technology that helped them exercise.

Discussion

The present study aimed to explore the effect of the UK lockdown during the Coronavirus-19 pandemic on access to exercise for people with blindness and visual impairments. To do so, we adopted a mixed methods approach. First, using two questionnaires to quantitively measure estimated weekly physical activity, and perceived barriers to participation, respectively. Secondly, we created open-ended questions to gain insight into specific barriers to exercise participation and how these barriers were (or might be) overcome. The EBBS questionnaire found that perceived barriers were highest during the initial UK lockdown (data collected between May 2020 and July 2020), and lowest during the later parts of the UK lockdown (data collected between November 2020 and February 2021). Perceived barriers to participation prior to the pandemic were in the middle between early lockdown and later lockdown. There were no significant differences between estimated METs from the IPAQ-SF in either lockdown stage or residence location. The thematic analysis suggested that the UK lockdown initially added extra barriers to participation to several already existing barriers specific (e.g., lack of specialised support or equipment) and non-specific (e.g., motivation and time commitments) to disability.

Combining the open-ended questions with the results for the EBBS questionnaire, it would appear that prior to lockdown, people with blindness and visual impairments tended to perceive typical and impairment specific barriers to exercise, such as lack of motivation, transport issues, and lack of accessibility support as previously reported in other studies (Ebben & Brudzynski, 2008; Gombas & Csakvari, 2021; Tappe et al., 1989). The implementation of the UK national lockdown added a greater number of barriers to exercise to those already existing, such as not being able to socially distance, and no longer having access to previous support. However, as the lockdown evolved and progressed some individuals began to use technological interventions, like online classes and social media, to facilitate exercise at home. In the early lockdown, the EBBS score was at the highest compared to both other stages. Based on open-ended feedback, this may have been primarily driven by the closure of exercise facilities as reported by many of our participants, and by the increased difficulty to exercise outside due to lack of support and social distancing measures. Indoor fitness training, like the gym, weights, and exercise classes were the most reported type of exercise that participants regularly took part in, which were all closed in the UK in the early stages of the lockdown (*Coronavirus Act 2020*, 2020). Interestingly, according to the EBBS score, there were fewer perceived barriers in the late lockdown stage than prior to the Coronavirus-19 pandemic. This data collection time frame took place when facilities had reopened in the UK but with social distancing measures in place. This, plus the open-ended feedback we received, may indicate that the faciliatory technology developed for exercise at home during the height of the restrictions, continued to be used alongside pre-pandemic exercise methods, thus increasing activity levels beyond pre-pandemic levels.

Our second hypothesis was that those living in highly built-up areas would have less access to exercise and more perceived barriers during rather than prior to lockdown. We did not find any significant differences for residential location on either EBBS score, or estimated METs. A possible reason for this is that our sample size was not big enough to allow for a suitable number of participants in each area of residence category. This is perhaps a side-effect of the unique possibility afforded to our study, in that our data collection spanned the societal change brought on by the pandemic, but limited opportunities to recruit the initially desired sample size. The extreme variation in IPAQ-SF scores also prevented the data from being conclusive. While others have reported successful uses of the IPAQ-SF for people with blindness or visual impairments (Matoso & Portela, 2020; Sadowska & Krzepota, 2015), the estimations of MET that the IPAQ-SF provides are not without fault. A systematic review found it to be a weak measure of total physical activity, and to often overestimate the amount of physical activity compared to more objective measures (Lee et al., 2011). However, due to its wide use in the literature, and the shortness of required response time, it is still perhaps the best estimate that can be obtained via remote questionnaire.

Our results offer further evidence that the pandemic severely affected those with visual impairments, complementing past research (Gombas & Csakvari, 2021; Mbazzi et al., 2020; Suraweera et al., 2021). Similarly, it may be possible to make the argument that those who regularly participated in exercise prior to Coronavirus-19 could not maintain exercise easily without the existing support systems on which they relied. As previously noted, people with blindness and visual impairments have reduced access to exercise (Capella-McDonnall, 2007; Matoso & Portela, 2020), and prior to lockdown, some of these factors included lack of disability-specific support, like gyms and exercise classes being unable to cater to those with low or no vision. For individuals that did manage to exercise at gyms or classes, the closure of these places during the pandemic greatly hindered access and social distancing during outdoor exercise created further barriers.

Further research would be best directed towards identifying the best ways to make virtual exercise sessions more accessible. Some efforts have already been made in this direction, experimenting with tailored audio feedback via camera (Rector et al., 2013), multisensory interfaces (Morelli, Foley, & Folmer, 2010; Morelli, Foley, Columna, et al., 2010), and increasing enjoyment and motivation through 'gamification' of exercise (Barathi et al., 2018). The gamification of exercise, through platforms such as Wii Sports or Xbox Kinect, has made a considerable impact on accessibility for people with injury or disability (Christine Higgins et al., 2010; Malone et al., 2016; Unibaso-Markaida et al., 2019). However, research is lacking on the inbuilt usability of these systems for those with visual impairments, and typically video games are designed for those with vision, unless specifically tailored otherwise (Gonçalves et al., 2021). We suggest that in the future it could be beneficial to devote research attention to exploring methods to increase playability of online exercise games for users with blindness and visual impairments. Additionally, validation of the IPAQ-SF and EBBS for people with blindness and visual impairments would strengthen the available tools for future investigations. Other more practical aspects of this study may be useful for designing more accessible exercise policies. For example, the participant that mentions that the local council-run gym would not allow exercise without a carer, points to a barrier that may be easily remedied with additional staff training and a more nuanced council policy on disability exercise.

Conclusion

The results of this mixed methods investigation suggest that, throughout the progression of the pandemic, access to exercise for people with blindness and visual impairments was initially severely impacted by the stay-at-home order. Thematic analysis offered further insights into the specific barriers to exercise participation. Suggesting that the closure of gyms and facilities, and difficulties with social distancing as a person with blindness or visual impairments, combined with existing barriers, such as lack of motivation and lack of specialised support, to greatly hinder access to exercise in the early stages of the UK lockdown. However, in the later stages of the pandemic, we found that people established new methods to exercise at home and outdoors, which combined with their existing pre-pandemic methods once facilities began to reopen. This led to fewer perceived barriers to exercise compared to pre-pandemic levels. Overall, we maintain that for maximum exercise accessibility for people with blindness and visual impairments, offering specialised virtual exercise sessions may be beneficial, but that these cannot replace in-person sessions.

Data Accessibility

An anonymised version of the basic demographic, EBBS, and IPAQ-SF responses and the analysis script are currently available at: https://osf.io/5f9zq/?view_only=cf9ab8ed93b54e8cbb2f4a35668c5b16 in a view-only format. Responses to the open-ended questions have not been included in the repository, due to the disclosure of potentially identifiable or personal information.

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Appendix A

Additional participant information including gender, vision status (registered blind or registered partially sighted), age, and age of impairment onset.

Stage	Gender	Vision Status	Age	Age of Onset
Pre-lockdown	Male	DNA	59	0
	DNA	Registered Blind	26	0
	Female	Partially Sighted	34	0
	Male	Partially Sighted	30	0
	Female	Registered Blind	47	29
	Male	Partially Sighted	17	0
	Male	Registered Blind	32	15
	Male	Partially Sighted	25	5
	Male	Partially Sighted	27	0
	Female	Registered Blind	37	27
	Male	Registered Blind	62	57
	Female	Registered Blind	36	0
	DNA	Partially Sighted	47	45
	Female	Registered Blind	40	0
	Female	Partially Sighted	23	3
	DNA	Registered Blind	DNA	DNA
	Male	Partially Sighted	40	38
	Male	Partially Sighted	58	47
	Female	Partially Sighted	45	30
	Male	Registered Blind	52	0
	Male	Registered Blind	43	42
Early-lockdown	Female	Partially Sighted	50	50
	Female	Registered Blind	45	3
	Male	Partially Sighted	70	63
	Female	Registered Blind	49	41
	Male	Registered Blind	51	0
	Female	Registered Blind	56	40
	Male	Registered Blind	18	0
	Female	Registered Blind	33	26
	Female	Partially Sighted	30	18
	Male	Registered Blind	29	12

	Female	Partially Sighted	18	5
	Male	Registered Blind	37	1
	Female	Registered Blind	41	19
	Female	Partially Sighted	28	19
	Female	Partially Sighted	45	35
	Male	Registered Blind	28	11
	Female	Registered Blind	24	20
	Male	Registered Blind	40	9
	Female	Partially Sighted	17	
	Female	Registered Blind	22	12
	Male	Registered Blind	63	59
	Female	Partially Sighted	55	50
Late-lockdown	Female	Registered Blind	25	19
	Male	Registered Blind	52	0
	Male	Registered Blind	64	58
	Male	Registered Blind	18	0
	Female	Partially Sighted	DNA	34
	Female	Registered Blind	41	0
	Female	Registered Blind	38	0
	Female	Registered Blind	47	25
	Male	Registered Blind	48	38
	DNA	Registered Blind	68	DNA
	Female	Partially Sighted	56	50
	Female	Partially Sighted	41	39
	Female	Registered Blind	58	4
	Male	Registered Blind	56	0
	Female	Registered Blind	49	0
	Female	Partially Sighted	24	3
	Female	Registered Blind	67	DNA
	Male	Registered Blind	48	38

Note. DNA = Did not answer.

General Discussion

The purpose of this thesis was to explore the potential suitability of tongue interfaces for increasing the access to exercise for people with visual impairments. The Introduction covered some of the previous research relating to tongue interfaces, sensory substitution, and current shortfalls in exercise accessibility for people with visual impairments. The literature suggested that SSDs, such as the BrainPort, may offer ideal technological hardware to improve the sensory capabilities of exercisers, but that the technology had not yet been applied for this purpose. Further, the literature highlighted a particular gap in fundamental knowledge concerning tongue interfaces, in particular, there was a lack of understanding in how spatial information can be perceived through the tongue. Past reviews on sensory substitution research indicated that a promising method to fill this gap in knowledge, is to conduct psychophysical examination through the substitution device. To this end, Chapters 1 and 2 explore the potential of a tongue interfaces to improve access to exercise; to generate critical knowledge that would help future device designers to tailor and modify SSDs for the purpose of sport and exercise.

Chapter 1 explored aspects of perspective-taking and individual differences, inspired by previous work with tactile attention on the body (Arnold et al., 2016, 2017). The studies by Arnold and colleagues (2016, 2017) suggested that people can take three major perspectives in response to ambiguous letters being traced on the torso (head-centred looking down; torso-centred looking out; and decentred looking back, respectively). Initially, we used this as a starting point, but quickly realised that the surface of the tongue posed more of a challenge than tactile stimuli on the body. As the tongue is horizontal and inside the head, there were instead four major perspectives that could be adopted (taking the view of ‘looking down’ from above to the tongue, versus, ‘looking up’ from below the tongue, and self-centred versus decentred perspectives). Additionally, perceiving information through the tongue can be challenging for participants (Nau et al., 2013; Pamir et al., 2020; Vincent et al., 2016); even providing each participant with 10 seconds to explore the display would not necessarily guarantee a successful response. Therefore, we opted to include trials from a range of difficulties, including straight lines as a basic measure of understanding, directional arrowheads as a medium difficulty, and the ambiguous letter stimuli (the letters ‘b’, ‘p’, ‘q’, and ‘d’) used in the graphesthesia task (Arnold et al., 2016, 2017), as the highest level of difficulty. Including these extra stimuli categories were deemed necessary in the case that any participants failed to identify any of the graphesthesia task stimuli, to provide some lesser measure of accuracy (i.e., to highlight whether participants could even identify straight lines) but did reduce the number of trials for each category of stimuli as a whole. The simpler stimuli also allowed us to draw parallels to past research (e.g., Grant et al., 2016), to ensure that our novice participants could successfully identify basic shapes. The results of the study indicated the participants could successfully complete the graphesthesia task via the BrainPort, showing that the tongue is a viable sensory organ to process complex visual information (such as letters), despite being horizontal in orientation and inside the head. However, the results are unpowered due to not enough repetitions of the graphesthesia stimuli. Future research could build on these results and focus solely on the graphesthesia task stimuli, and therefore, utilise a greater number of trials while keeping the experimental session short enough to ensure no fatigue effects take place. Likewise, the low power prevented the regression analysis on potentially influencing personality traits from being particularly insightful, but also may offer some rough directionality for future work to build on.

Including the arrowhead stimuli in Chapter 2 had an unintended consequence that became one of the more intriguing findings of the study. In that, participants seemed to change their perspective from self-centred to decentred depending on where the arrow was pointing (split between left/right arrows, and up/down arrows). This finding led us to conclude that perhaps task-related differences may also be in play while perceiving spatial information through the BrainPort. It was also a direct inspiration for an avenue of exploration in Chapter 2; does the way the BrainPort flip information on the vertical axis impinge on perceptual ability?

Chapter 2 applied the Posner Cueing Paradigm (Posner, 1980), a design that has greatly informed on current models of attention (Spence & McGlone, 2001), to the tongue. In traditional research using the Posner Cueing Paradigm to explore exogenous attention (also known as bottom-up or reflexive attention, as it relies on peripheral sensations to capture attention with cueing information), cues and targets are divided into two lateral sides; ipsilateral trials (cue and target information appear on the same side) and contralateral trials (cue and target information appear on opposite sides). However, like in Chapter 1, when considering how to best apply this psychophysical methodology to the surface of the tongue via the BrainPort, some extra thought was required. Using Spence and McGlone's (2001) seminal work on non-predictive (the cue does not predict the exact location of the target, but merely indicates a potential area in which the target may appear) exogenous tactile attention with the hands as a starting point, we considered how to best apply this to the tongue. Dividing the tongue into four quadrants provided the opportunity to not only investigate non-predictive exogenous attention on its surface, but to also gain some quantification of the difference of attentional capacity between the front and back sections. Again, much like Chapter 1 the addition of extra conditions reduced the feasible number of trials undertaken in each stimulus category. In this study we split participants into different between-subject groupings to maintain a high number of trials for each group. This meant that within-subject analysis was strong (as was the initial focus), but weak when considering mixed- or between-subject effects.

Through the studies in Chapter 1 and Chapter 2, it became apparent that using the tongue as an interface requires careful consideration. Information can be perceived differently depending on the individual or the task, and the attentional capacity of the tongue can be overloaded without recruiting additional modalities to share the perceptual load. Given these considerations, a device such as the Cthulhu Shield may be a highly suitable alternative to the BrainPort. As an Arduino-based device, it is customisable (and therefore easy to adapt to the task or the individual), cost-effective, and although it has far less electrodes, this may not be of consequence due to the ease of overloading tongue interface users. Additionally, the methods used in Chapters 1 and 2 provided a valuable lesson for future work; it is more efficient to minimise the number of factors in any paradigm, to focus on repetitions, and ensure sufficient recruitment strategies are in place for exploratory studies to allow for more powerful analysis of additional factors. In this instance, the results of Chapter 1 were analysed during the beginning of the data collection in Chapter 2, which created the question concerning the potentially highly influential factor of the BrainPort's manipulation of vertical space (which was subsequently added into the design of Chapter 2, reducing the number of participants in each between-subject group).

Chapter 3 faced a highly confounding factor part way through data collection: Coronavirus-19. After consideration of how to handle this change in societal functioning, we deemed it appropriate to change the scope of the study to factor in the effects of the pandemic. Chapter 3 therefore became an exploratory analysis of the impact of the nationwide lockdown on access to exercise for people with visual impairments. In the cases of Chapter 1 and Chapter 2, some unexpected results were uncovered. To help illuminate any potentially unusual results in this study, we chose to also use some qualitative questions in addition to established psychometric scales. This mixed method approach offered strengths from both quantitative and qualitative research and has been touted as a preferential approach to research in some cases (Almalki, 2016; Doyle et al., 2009;). The results of the study demonstrated that technological interventions were adopted by people with visual impairments during the pandemic, and this led to a reduction in perceived barriers to participation. It also found that, generally, barriers to participation were high even before the pandemic. The most common barriers to participation were factors such as lack of transport, lack of accessible facilities and lack of specialised instruction. When the UK national lockdown was implemented by the UK government barriers increased, as existing support structures were disrupted and people with visual impairments could no longer access carers or facilities to enable exercise, and exercise alone (as was set out in the Coronavirus 2020 Act) was not possible due to sight impairments. This result parallels other research that occurred during the pandemic, in that people with visual impairments and disabilities were more severely impacted by lockdowns in a number of countries (Gombas & Csakvari, 2021; Senjam, 2020; Ting et al., 2021). However, over the course of the pandemic new methods for exercise assistance were developed, such as using video conferencing software for specialised exercise classes with increased auditory feedback. These methods then compounded with previously existing exercise support systems, once the lockdown was partially lifted, leading to a reduction in exercise barriers compared to pre-pandemic levels. Some participants reported instructor-led exercise classes from home were challenging, or not possible, due to a lack of suitable output display for the classes, possibly, alluding to the need for accessible non-visual displays.

Sensory substitution has been remarkable for its contribution to understanding brain plasticity and sensory processes and developing novel computer interaction methods (Amedi et al., 2001, 2007; Nau et al., 2015). However, while the field has an impressive resume in laboratory and academic settings, no single sensory substitution device has yet to see widespread uptake and use from its typical intended end-user group (Maidenbaum et al., 2014). One such reason for this could be due to high expectations of a ‘sensory substitution' device, and respective disappointment (Lloyd-Esenkaya et al., 2020); the very definition of substitution implies little-to-no quality loss. Vision is an incredibly high bandwidth sense, and there is typically a great deal of information loss in the substitution process (Richardson et al., 2019). SSDs are typically programmed to filter out some information to prevent overload, for example, colour, depth, or reduction of image resolution. Once the visual information has been downscaled into more interpretable sensory data, the SSD user still relies on perceptual processes to attribute the raw sensory data in environmental phenomena (Auvray et al., 2005, 2007; Hartcher-O'Brien & Auvray, 2014; Segond et al., 2005; Siegle & Warren, 2010). A review of technological devices for people with visual impairments suggested that SSDs are yet to be widely accepted due to a number of reasons, including invasiveness (blocking a depended-on modality, such as hearing or impinging on speech), cognitive overload (too much information for the modality), and intensive training requirements (Gori et al., 2016). However, in the context of other generalised visual-assistive technologies, SSDs still have a role to play, if their implementation is carefully considered; particularly, when compared against other viable general vision aids.

Retinal prosthesis is a method of vision restoration that has been gaining some traction over the past decade, with particular reference to the Argus II Retinal Prosthesis System (Second Sight Medical Products, USA) becoming the first device to obtain commercial market approval. The Argus II directly stimulates the inner retina via epiretinal microelectrodes, essentially bypassing the photoreceptors (Luo & da Cruz, 2016). As such, the device is primarily used for those with retinitis pigmentosa or other outer retinal diseases and cannot be used for any type of vision loss that results from optical neural dysfunction, cortical damage, or inner retinal degradation. Other types of vision prothesis are being developed which stimulate further down the visual pathway (Beyeler et al., 2017), however these are yet to enter the available market and still require some visual development, making them inaccessible for those with congenital blindness.

While research with the Argus II is still recent and developing, to date, functional performance of the device is somewhat limited compared to SSDs, although a formal review is yet to be conducted. The implant and training process is longer, more intensive, and invasive than SSDs, and actual device performance appears to lag behind both the BrainPort and the vOICe (Chebat et al., 2007; A. Nau et al., 2013; Striem-Amit et al., 2012; Zrenner et al., 2011). The perceptual experience offered by retinal prostheses is often referred to as phosphene vision and is typically low-resolution spatialized patterns of light. Simulation studies suggest that increasing the number of electrodes may increase performance with the device (currently the Argus II has a 6 × 10 array of electrodes), although another prothesis utilized a 38 × 40 array of electrodes (Zrenner et al., 2011), and like with SSDs, massively scaling up pixel density does not necessarily increase perceptual ability by the same factor.

Sensory substitution may offer a way to improve the functionality of phosphene vision. The vOICe, in combination with simulated phosphene vision, can increase light localization ability compared to relying solely on one or the other (Kvansakul et al., 2020). However, in the same study, the vOICe offered a higher resolution perception, and no improvements were found by combining the modalities together. At the time of writing, there were no studies utilising the BrainPort in combination with phosphene vision. As retinal prostheses are currently expensive and require invasive implant surgery, the better resolution offered by the free-to-use vOICe, or cheaper BrainPort, should be highly appealing for those in the market for vision assistive technologies. The results demonstrated in Chapter 1 and 2 show a more refined perceptual ability than much of the current work with prosthesis devices. Chapter 3 suggested that, while some people with visual impairments are happy to adopt new technology, its usability is major factor, as is cost. Yet, those who use a prosthesis report improved quality of life with the device (Vaidya et al., 2014), perhaps indicating that an intrinsic property of visual feedback, regardless of how minimal, is inherently rewarding. Perhaps an inherent problem with a tongue display is that the feedback is too dissimilar to what a visual-like experience is perceived to be by a visually impaired user, especially for a late blind user that has comparable past visual experience. An alternative, and rapidly developing, field that may provide useful tools for vision assistance can be found in machine learning and computer vision.

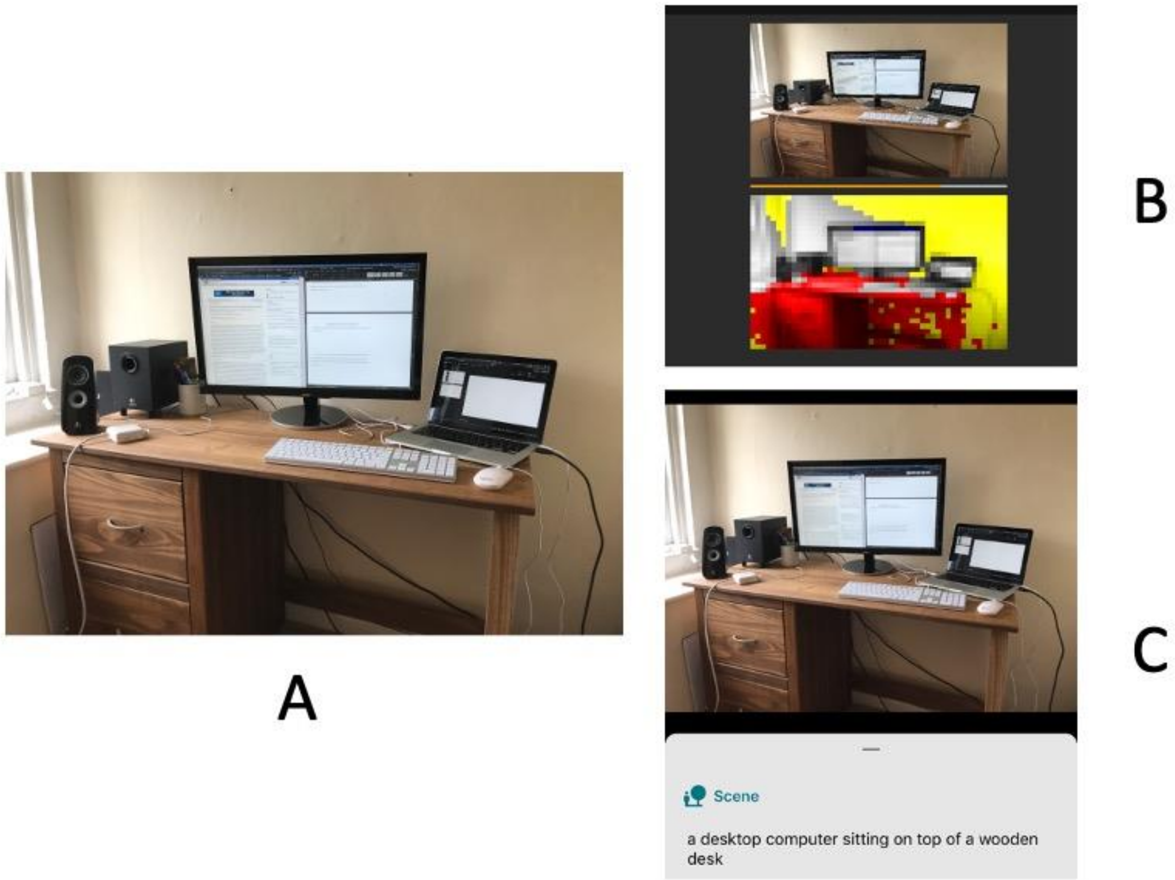
Computer Vision or Sensory Substitution?

Computer vision (CV) and artificial intelligence (AI) research have seen growth in recent years (Voulodimos et al., 2018), arguably due to the growing availability of high-quality low-cost commercial sensors and improvements in computer processing (Han et al., 2013). In terms of vision assistive technologies, much like many SSDs, programmers have opted to utilise the practicality of smartphone processing. Two major smartphone applications are Seeing AI (Microsoft, WA, USA) and TapTapSee (TapTapSee, USA). The hardware requirements between a CV device and an SSD are remarkably similar, as both require a sensor, a processor, and an output. However, where a SSD tends to convey a downscaled version of information through a different sensory channel, these programs only convey features of the image which were deemed useful by its programming and are subsequently relayed through descriptive language (see Figure 1 for a comparison of image interpretations). Descriptive language may at first seem advantageous over a percept of encoded information, for example, it requires no prior learning past basic language comprehension and can convey highly specific details concisely (for example, in Figure 1, the wooden-ness of the desk). However, an image holds a great deal of information and the medium of language, while flexible, may suffer with lacking information (in the pursuit of increased speed of conveyance), or lack of responsiveness to situational change (in the pursuit of detailed information). This latter problem is particularly pertinent for sport and exercise, where spatial stimuli occur and change rapidly.

A prototype device, called PeopleLens, has been making efforts to combine aspects from sensory substitution and AI approaches into one, for the purpose of identifying and locating people in a classroom setting. The PeopleLens is based on the Microsoft HoloLens hardware (Morrison, Cutrell, Grayson, Becker, et al., 2021; Morrison, Cutrell, Grayson, Roumen, et al., 2021), and amalgamates computer vision and descriptive language, with sensory substitution concepts. The PeopleLens uses computer vision to identify different people and verbally tells the user the name of individuals recognised (Morrison, Cutrell, Grayson, Becker, et al., 2021), a highly difficult task for a SSD to accomplish. However, for locating people or objects in space, descriptive language is less efficient. Therefore, the PeopleLens helps users to orientate themselves using spatialised audio, rather than language. We suggest that, like PeopleLens, the future of sensory substitution outside of laboratory settings may need to be tailored to incorporate other technologies to help provide the most informative and usable transformation of visual information. It is impossible to convey visual scenes through other modalities without data loss and computer vision and machine learning algorithms can help to identify useful features. This would make the substitution process far more targeted and effective, a particular benefit for exercise, where device users are exposed to a great deal of uninformative information.

Figure 1

Comparing a sensory substitution and computer vision approaches to relaying visual a visual scene to a smartphone user.



Note: A = original photo of a computer on a desk. B = eyeMusic conversion of image into simple coloured pixels. C = Microsoft's 'Seeing AI' interpretation of the image using its scene analysis function with text reading 'a desktop computer sitting on top of a wooden desk'.

There is certainly a case for providing simplified spatial information rather than the traditional total replacement of vision that devices like the BrainPort attempt to translate. To illustrate, the Audio Bracelet for Blind Interaction (ABBI) device is designed to rehabilitate spatial cognition in children (Finocchietti, Baud-Bovy, et al., 2015; Finocchietti, Cappagli, et al., 2015; Porquis et al., 2018). Where the BrainPort, may be overstimulating for young children as it converts full images into haptics, the ABBI device has a specific and targeted implementation. Instead, the ABBI device is worn around the wrist or ankle and provides auditory feedback to facilitate proprioceptive calibration in place of the visual system. This specific and targeted use of auditory feedback reduces sensory overstimulation and increases device use, ultimately leading to improved spatial skills in children with visual impairments (Cappagli et al., 2019). The same principles can be applied to a more general substitution device using an AI component to select important visual features. Applied to a sporting context, an object detection algorithm could be trained to detect climbing holds or slalom gates and the SSD component could relay this information through an alternative modality. Much like the previously discussed PeopleLens, combining approaches from sensory substitution with AI may mitigate some of the problematic aspects from either field. AI could reduce the volume of information needing to be substituted preventing overstimulation, and the SSD can provide a direct stream of perceptual information rather than relying on descriptive language that AI programs typically output. Again, to successfully substitute one sense into another even with AI filtering the useful information, it is still critical to understand the upper limits set by an interface and corresponding modality, to ensure that the AI provides the maximum amount of perceivable information without overloading the user. In the case of the BrainPort, understanding how perceptual processes operate on the tongue in response to substituted visual information is critical to ensure maximum usability, within the limitations set by both the receptor (the tongue) and the interface (electrotactile stimulation).

We suggest that the specific and targeted uses of sensory substitution may have a greater likelihood of uptake compared to past SSDs that convert full images. The process of substituting vision arguably causes too much sensory noise (Gori et al., 2016; Kristjánsson et al., 2016; Maidenbaum et al., 2014), with non-features given the same weight as visual features (Brown et al., 2014; Brown & Proulx, 2016). If all the sensory modalities had the same information processing capacity this would be irrelevant with training and practice. However, since each modality has different data processing abilities and all suffer information loss compared to vision (Haigh et al., 2013; Richardson et al., 2019), the method of substituting an entire image potentially wastes processing bandwidth.

Future Directions

The empirical work presented in this thesis provides a substantial depth and breadth of knowledge from which programmers and engineers can draw from, to create new and task specific tongue interfaces. Future device designers will know and understand some of the perceptual limitations that exist with using the tongue as a medium for substitution, and likewise, know that there is a desire within communities of people with visual impairments for novel exercise technology. Typically, this following section of the thesis would now describe future directions for implementing the knowledge presented here. However, in the place of a ‘Future Directions’ section, this thesis instead introduces Chapter 4, *Climb-o-Vision: A Computer Vision Driven Sensory Substitution Device for Rock Climbing*. Chapter 4 demonstrates one potential avenue for implementing the knowledge generated from this PhD programme, as the Climb-o-Vision system directly draws on the work from the previous chapters. Climb-o-Vision is presented here as a tentative prototype, combining a tongue interface with AI approaches, to develop a highly novel and task specific exercise aid.

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Chapter 4 Statement of Authorship

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Formulation of ideas: 90%

Design of methodology: 90%

Experimental work: 100%

Presentation of data in journal format: 90%</td></tr>
<tr><td>Statement from Candidate</td><td colspan="3">This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.</td></tr>
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Chapter 4: Climb-o-Vision: A Computer Vision Driven Sensory Substitution Device for Rock Climbing

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Abstract

The benefits of taking part in adventurous activities are many; particularly, for people with visual impairments. Sports such as rock climbing can improve feelings of skilfulness, autonomy, and confidence for people with low or no vision as they strive to overcome environmental and personal challenges. In this late-breaking work we present Climb-o-Vision, a novel sensory substitution software that utilises YOLOv5 computer vision object-detection architecture, to aid navigation for rock climbers with visual impairments. Climb-o-Vision uses commercially available and cost-effective hardware to detect, track, and convert climbing hold spatial locations on to the surface of the tongue, via an electrotactile tongue interface. Preliminary testing of the device highlights the possibility of using sensory substitution as a sporting aid for people with visual impairments. Furthermore, it demonstrates the potential for adapting and improving current sensory substitution systems by employing computer vision techniques to filter useful task-specific information to users with visual impairments.

Keywords: sensory substitution, computer vision, accessible sport, rock climbing

Introduction

Access to exercise for people with visual impairments is reduced compared to others (Capella-McDonnall, 2007; Matoso & Portela, 2020; M. Richardson et al., 2022). As such, many people with visual impairments often suffer with comorbid health issues relating to insufficient exercise (Shields et al., 2012). For many years, targeted applications of technology have been deployed to help increase participation in sport and exercise for people with disabilities (Thomas & Smith, 2008). For instance, Blind Football, Goalball (a ball game designed specifically for people with visual impairments), and Visually Impaired Tennis all utilise a ball that creates noise when in motion. For target sports, such as archery, often a tactile or auditory 'sight' can be used to align the participant's shot (*Archery - British Blind Sport*, n.d.). More recently, the field of human-computer interaction (HCI) has helped to develop novel prototype devices that further expand exercise possibilities to less 'typical' sports, such as hiking or kayaking (Anthierens et al., 2018; Long et al., 2016).

Exergames, video games that involve an exercise component to play or progress (Oh & Yang, 2010), are becoming increasingly popular, particularly since the development of interactive console hardware such as the Nintendo Wii and Xbox Kinect (Hall et al., 2012; Willems & Bond, 2009). HCI research has generated interesting prototypes from exergames and exergame concepts specifically created for people with visual impairments. Notably, a team developed VI-Tennis and VI-Bowling (Morelli, Foley, & Folmer, 2010; Morelli, Foley, Columna, et al., 2010) exergames built on Wii Sports, but with additional tactile and audio feedback to improve players' experiences. However, exergames may lack many of the positive features of sports, such as social development and benefits associated with being in a dedicated exercise environment (Martin, 2006; Mutz & Müller, 2016; Seymour et al., 2009). This is particularly the case for adventurous sports, where an individual tends to compete against the environment itself, or themselves, rather than another person or team. For example, in rock climbing, a major component of the sport involves using balance and stability to maintain traction on small holds off the ground, in a competition against gravity. Virtual climbing simulators struggle to successfully emulate this critical component as the feet tend to remain on the floor in virtual settings (Jenny & Schary, 2015).

HCI research also offers technology to help exercisers with visual impairments increase their participation in more naturalistic exercise environments; for example, by attaching sound emitting devices to slalom gates to help kayakers navigate (Kirtland et al., 2013), or to climbing hold locations to help rock climbers orientate themselves (Ilich, 2008). Adventure sports such as these can increase feelings of confidence, resilience, and generate supportive relationships (Jessup et al., 2010; Macpherson, 2009; Schroeder & Weihenmayer, 2002); however, manipulating the environment with sound emitters may have some drawbacks. Each emitter must first be placed into the environment and subsequently moved or changed for each new variation of the activity or route. This immediately reduces accessibility as there must be at least one additional individual available to provide support, and drastically slows the rate at which a person could perform different routes, which may limit feelings of autonomy and skilfulness (Deci & Ryan, 2000; Ryan & Deci, 2000), and impede positive associated mental states, such as flow and creativity (Nakamura & Csikszentmihalyi, 2014; Wang, 2012). Furthermore, inside climbing gyms, routes are frequently 're-set' to create more variety for climbers but limits the feasibility of fixed navigation methods (like learning a tactile map).

Here, we present a new prototype software approach, called Climb-o-Vision (see Figure 1), that uses computer vision and sensory substitution to convey climbing hold locations in a climbing gym via a tongue interface (the Cthulhu Shield), without the need to adapt the environment or simulate the activity virtually, while also leaving the ears and auditory modality unoccluded (an important safety feature for climbing).

Related Work

The concept of Climb-o-Vision was inspired by sensory substitution research, specifically, previous research with a different tongue interface, the BrainPort (Wicab, WI, USA). The BrainPort is an FDA and CE approved vision-into-tactile sensory substitution device (SSD), marketed as a vision aid for people with severe visual impairment (Grant et al., 2018). It converts visual information from a camera mounted on the forehead to electrotactile stimulation on the tongue. The tongue display consists of a 20×20 grid of electrodes (minus 6 corner electrodes), with each electrode representing a pixel and encoding luminance as amplitude of signal, in essence, creating a 394-pixel greyscale display on the surface of the tongue.

Figure 1

Climb-o-Vision in use (left). Climbing hold identification visual render (centre). The Cthulhu Shield tongue interface output device (right).

Past research with the BrainPort has offered some compelling results for tasks, such as shape identification and navigation (Grant et al., 2018; Nau et al., 2015; Stronks et al., 2016), however, this is often caveated by a user's performance being dependent on having enough time to actively explore the display with their tongue (Pamir et al., 2019). This may be potentially problematic when using the BrainPort for sporting purposes as environmental interaction needs to be rapidly adaptive in response to change. The BrainPort has previously been used for the purpose of rock climbing by adventure sport athlete Erik Weihenmayer (Twilley, 2017), but this is yet to be adopted by others, or reflected in academic literature.

The tongue presents both unique possibilities and challenges as a receptor for sensory substitution. For instance, the tongue is incredibly sensitive to touch sensations, but is not uniform in its sensitivity (Haggard & de Boer, 2014; Sakamoto et al., 2010). The anterior section possesses a better capacity for electrotactile sensation compared to the posterior section (Allison et al., 2020; Moritz Jr. et al., 2017). Because of this, information presented to the posterior of the tongue's surface is generally less well perceived (Pamir et al., 2020). Additionally, visual information occurs in the vertical plane, perpendicular to gaze, while the surface of the tongue is aligned on the horizontal plane, meaning perception must be mentally rotated by 90° either forwards or backwards (M. L. Richardson et al., 2020). The BrainPort rotates information so that the top of the camera's field of view (FoV) is presented to the posterior section of the tongue and the bottom of the FoV to the anterior section. The perceptual sensitivity gradient on the tongue means that information at the bottom of the camera's FoV will be more accurately identified (Pamir et al., 2020), and attentionally prioritised, compared to information at the top of the FoV. For climbing, this is particularly an issue, as navigation typically occurs while ascending.

One of the common issues of SSDs is that they can overload the user with too much information (Brown et al., 2014; Brown & Proulx, 2016; Gori et al., 2016). Vision is the highest bandwidth sense (Richardson et al., 2019), which inevitably means perceptual loss when substituting information. Many SSDs, such as the BrainPort, currently deal with this issue by downscaling the information prior to substitution, for example, by reducing pixel density, removing colour, or narrowing the camera's FoV. However, in the case of the tongue, this method may not be enough to counteract the sensitivity gradient. We argue that computer vision techniques can be applied to current sensory substitution systems to filter out task-relevant information and help prevent overstimulation, to create task-specific devices, and in this case, increase the available opportunities for accessible exercise.

Climb-o-Vision Prototype

In this section we put forward the prototype SSD, called Climb-o-Vision, that uses computer vision to identify climbing hold locations and then it converts the spatial information into tactile stimulations on the tongue. This prototype consists of commercially available and affordable devices (namely, the Cthulhu Shield for Arduino, an Arduino Uno, and a USB webcam), that connect to a laptop running the Climb-o-Vision program, stored in a backpack while climbing.

Hardware

The Cthulhu Shield (Sapien LLC, CO, USA) is an Arduino compatible tongue interface that utilises an 18-electrode grid that, like the BrainPort, can write information to the tongue (but unlike the BrainPort can also read information from the tongue, a feature not used here). For the Climb-o-Vision prototype, we used the device as a display to stimulate the tongue with spatial information depending on climbing hold location. The Cthulhu Shield is driven by an Arduino Uno (Rev 3, Arduino, Italy), which is then connected to a computer via a serial port. The Cthulhu Shield was chosen over the BrainPort for a number of reasons, including, its accessible and customisable open-source programming, and cost effectiveness (it is approximately 1% of the price of the BrainPort).

The Climb-o-Vision software can run on any laptop with enough processing power, the version demonstrated here used a MacBook Pro (2020, Apple M1, 16GB RAM) running on macOS Big Sur (Version 11.4). Likewise, the program could use any external USB camera, however, the webcam used here was the NexiGo N60 (1080p, 30fps, USB 2.0). The climbing hold detection model was trained on an Alienware Area-51 R2 PC, with an Intel® Core i7 (5820k @ 3.30GHz), 16 GB of RAM, running on Windows 10 (Microsoft, WA, USA), and utilising a Nvidia 1080 Ti graphics card, allowing for CUDA (version 10.2.89) optimisation of the model training.

Software

The software was developed in Python 3 and predominately utilizes PyTorch (version 1.9.0) and YOLOv5 (Ultralytics) object detection architecture (*GitHub - Ultralytics/Yolov5: YOLOv5 🚀 in PyTorch > ONNX > CoreML > TFLite*, n.d.). YOLOv5, the fifth version of the seminal detection architecture 'You Only Look Once' (Redmon et al., 2016), is pretrained using the Common Objects in Context (COCO) dataset and can then be adapted with custom categories (Lin et al., 2014). The program uses the OpenCV library (version 4.5.2) to perform image processing and apply the model frame by frame. A copy of the program file can be found here: (*https://tinyurl.com/yck93jyd*).

We programmed the software to only provide lateral cues for hold location to bypass the issue created by the tongue's sensitivity gradient. To do this, we restricted each video frame's aspect ratio from 16:9 to 8:1 (800:100 pixels), creating a narrowed vertical field of view (FoV), meaning that the user must estimate verticality through active sensing by moving their head up and down. This method of substitution reduces the problematic posterior section of the tongue, by providing the same lateral information to both the anterior and posterior sections and allowing the user to solely attribute lateral cues in line with their head. A restricted FoV has been employed by other SSDs to encourage users to actively explore the environment and to minimise overstimulation (Hamilton-Fletcher et al., 2021; Maidenbaum et al., 2014).

Model Training and Validation

To collect the training image dataset, video files were captured via the webcam mounted to a climbing helmet. Video clips were captured during the process of climbing on bouldering routes inside a climbing gym to maintain use-case validity. Each video file was broken down into individual frames and one frame in every sixty was recorded into the training image file (i.e., one frame for every two seconds of video), creating 565 images in total. For each of the training images, an accompanying annotation file was created using LabelImg (Tzutalin, 2015), that marked the coordinates of each climbing hold. YOLOv5 then divides the dataset into two, creating batches of training images, and batches of validation images (see Table 1 for model performance, and Figure 2 for a sample validation batch).

In climbing gyms, different routes are typically designated by their coloured holds. An issue with using the BrainPort for climbing, is that it only presents visual information in greyscale, so while it may be possible to correctly identify the hold location with practice, it would be far more difficult to correctly identify one route from another (see Figure 3C for an example of this). For the present version of Climb-o-Vision we focused on five categories of route colour to maintain simplicity, however, this can easily be scaled up in future versions of the program. We chose to use three colour categories: red, yellow, and green, respectively, and two multi-coloured categories: orange/green swirls, and black with green spots.

The smallest and fastest pretrained model was selected (YOLOv5s) to increase the speed of the training phase, and the model was trained using the settings: image size = 320 pixels; batch size = 16; workers = 1; epochs = 500. Table 1 shows the performance metrics at various epochs throughout the training process (100^{th}, 200^{th}, 300^{th}, 400^{th}, and 500^{th} epoch, respectively); precision and recall metrics were high even by the 100^{th} epoch, while mean average precision (mAP) progressively improved throughout, and by the 500^{th} epoch, offered a good indication of accurate model performance. Precision, recall, and mAP are common markers of object-detection performance (Redmon et al., 2016; Redmon & Farhadi, 2018).

Table 1

Model performance metrics.

Epoch	Precision	Recall	mAP@.50:.95[a]
100	0.931	0.964	0.753
200	0.987	0.983	0.813
300	0.996	0.993	0.856
400	0.997	0.996	0.896
500	0.997	0.998	0.913

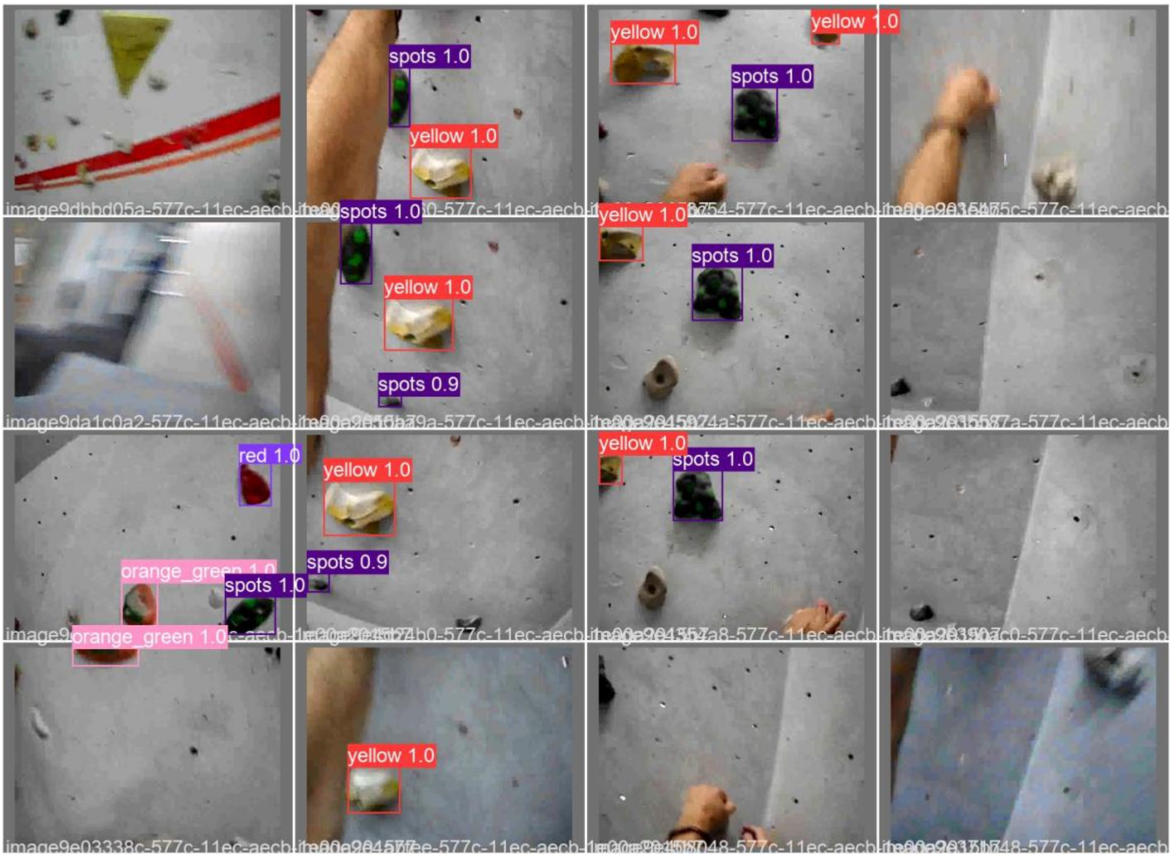
Note: [a] Mean Average Precision at an Intersection over Union (IoU) thresholds of .50 to .95; a common performance indicator for the Common Objects in Context dataset. All metrics have a range of 0 to 1.

Simulated Testing Phase

To initially test the performance of the model after training and validation we ran the program on pre-recorded video from which the training and validation dataset was originally compiled (the training dataset contained one frame in every sixty, meaning the remaining 59 were novel). This phase demonstrated that Climb-o-Vision could successfully apply the model to frames that were captured in the same conditions with the same holds, but that were not used in the model's training or validation, and therefore, were novel to the model (see Figure 3D). Inspection of the rendered video file demonstrated that the model could successfully be applied to new frames, but that a degree of overfitting existed, where some hold colours that had been excluded from the model were mis-identified as colours that were included in the model (e.g., predicting that pink holds were red). The model's inference speed results were: 0.2 ms pre-processing; 98.5 ms inference; 0.2 ms non-maximum suppression (NMS) per image at shape (1, 3, 320, 320).

Figure 2

A sample batch of validation images and predictions created by YOLOv5 during the hold detection training process. Each batch contained 16 images, each with a resolution of 320 × 240 pixels.



Applicative Test Phase

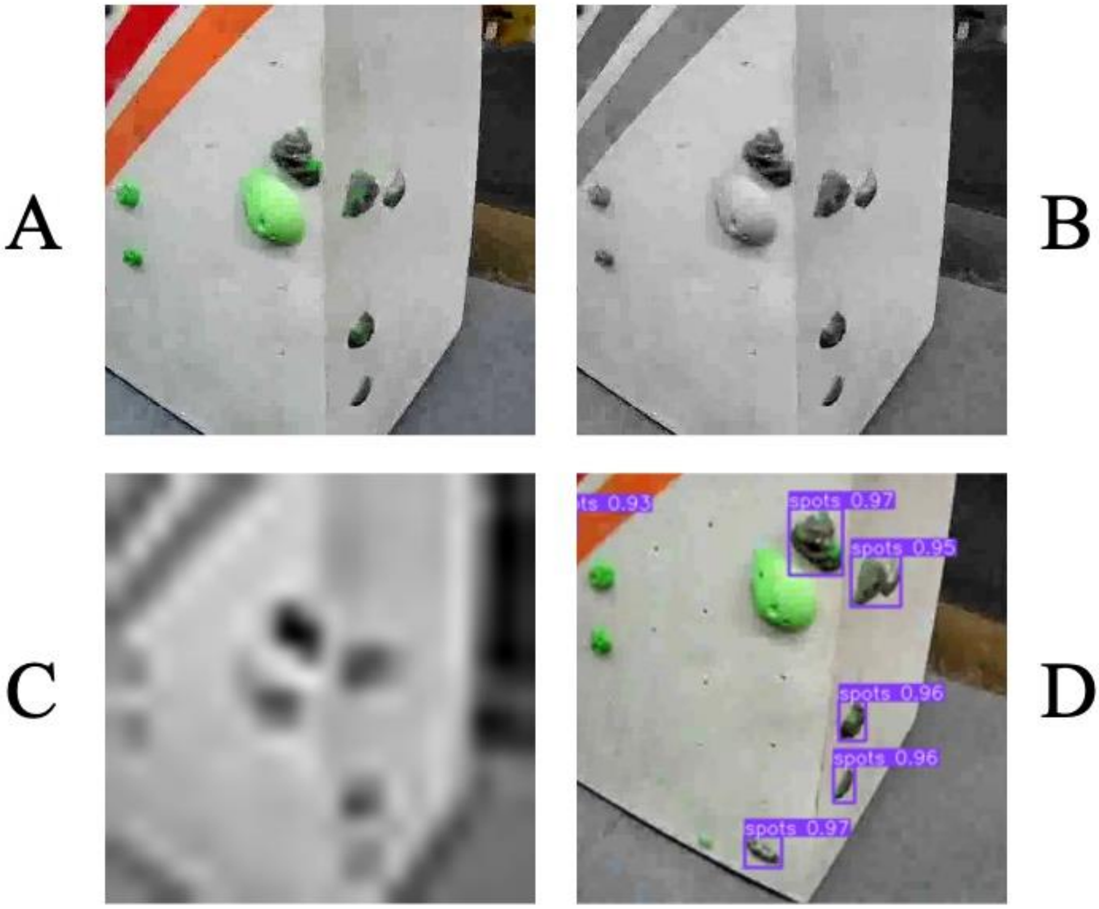
To test the model's actual performance, we took Climb-o-Vision back to the climbing gym after routes had been re-set. The re-set enabled us to test the program on new holds in different positions and in real-time. We found that Climb-o-Vision could still successfully detect climbing holds despite frames containing different holds in different locations (see Figure 4), and therefore, were more novel to the model than the pre-recorded video. However, we observed that the overfitting seemed to occur more frequently than the pre-recorded video. Many excluded colours were mis-identified as included colours, and for some frames, the model mixed up trained colours (e.g., identifying red holds as yellow), perhaps due to slightly different lighting conditions (Acunzo et al., 2007). This would be problematic for the user, as they could be directed to a hold colour that is not part of their intended climbing route. Interestingly, the model identified holds with different coloured spots quite robustly, perhaps suggesting that multi-toned holds are easier for the detection process.

Discussion

The Climb-o-Vision prototype demonstrates that computer vision techniques can be successfully applied to sensory substitution for the purpose of sport and exercise, creating task-specific applications that filter out useful information. The present prototype focused on the sport of rock climbing, as tongue displays have been utilised for this activity before in popular media (Levy, 2008; Twilley, 2017). More importantly, rock climbers with blindness and visual impairments also often mention the positive impact of participating in an adventure sport (*The Art of Climbing - RNIB - See Differently,* n.d.), particularly on boosting confidence and overcoming fear associated with sight loss (*The Art of Climbing - RNIB - See Differently,* n.d.). However, despite rock climbing taking the present focus, there is no reason why a similar method could not be applied to other sports. The field of sensory substitution can offer unique non-visual displays that translate important visual features from a given sport (e.g., other players in football/soccer, a ball in goalball, obstacles while trail running), which can be highlighted by custom trained object detection architecture. Computer vision techniques have been integrated into a vision-into-audio SSD previously for the purpose of alerting the user to approaching hazards (Gomez et al., 2014), and likewise spatialised audio principles have been applied to computer vision devices for orientating the user to another person (Morrison et al., 2021). Climb-o-Vision represents the next logical steps of combining these two fields to develop a wider scope of visually assistive technology.

Figure 3

Demonstrating potential interpretations of climbing route navigation using restricted information.



Note: A = an unprocessed video frame of two separate climbing routes; B = a greyscale version of the frame, where the lighter colour and darker colour separate the routes; C = the greyscale frame rendered to 400 pixels, as the BrainPort would display to its user; D = the frame with object detection applied, highlighting a single route, as would be displayed to the Climb-o-Vision user.

Limitations

To reduce file size and increase processing time, the model was trained using low resolution images, however due to the size and shape of climbing holds, we expect that increasing the image size would increase the detection performance, and prevent the model overfitting (i.e., reduce the likelihood of misidentifying non-climbing holds as climbing holds). Furthermore, during applicative testing we found that the model regularly mis-identified holds with the wrong colour. To combat this, we aim to train future versions of the model with a larger and more varied dataset, including images from different climbing walls in diverse lighting conditions. Increasing the number of categories to encapsulate more colours of climbing hold should also help to prevent the model from misidentifying the incorrect colour (e.g., by differentiating pink holds from red, or grey holds from black).

Future Directions

The further next steps for Climb-o-Vision are twofold. Firstly, we plan to objectively evaluate climbing performance with the device, compared to the BrainPort, and self-motion, to give an indication of how it performs compared to traditional navigation methods for rock climbing (self-motion), but also compared to a non-computer vision tongue interface (BrainPort). To do this we will recruit rock climbers with blindness and visual impairments to test how Climb-o-Vision affects their current navigation strategies while rock climbing, and we will also recruit non-climbers to examine how it influences the learning process of climbing. Secondly, we aim to improve the hardware constraints of Climb-o-Vision. Currently, the software operates on a laptop stored in a rucksack while climbing, however, this adds additional weight to the climber. We hope to utilise modern powerful mobile processing, as other vision aids have done (Hamilton-Fletcher et al., 2021; Morrison et al., 2021), to reduce weight and increase the usability of the device.

Figure 4

The model overfitting trained hold categories onto untrained hold colours.

We also hope that the field of sensory substitution begins to seriously consider the use of computer vision for improving generalised SSDs, and vice versa for computer vision assistive devices. SSDs can provide the ideal technology for intuitive non-visual displays (Lloyd-Esenkaya et al., 2020), while visually assistive applications, such as SeeingAI (Microsoft, WA, USA), can provide a selective filter for incoming information; both fields can improve from mutually beneficial collaboration.

Conclusion

This late-breaking work demonstrates the concept that computer vision techniques can be successfully applied to the field of sensory substitution to improve sport and exercise opportunities. Computer vision can help to filter out background or irrelevant information that could potentially overload SSD users, particularly for specialised activities. While Climb-o-Vision has more refinements required before it is useable as an assistive technology, it marks the first steps towards unified and targeted approach of vision assistive technologies for increasing access to exercise.

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Closing Summary

In the Introduction, this PhD thesis suggested that sensory substitution may offer novel technological applications to help increase access to exercise for people with visual impairments. It covered some of the previously highlighted problems with existing SSDs, most notably, issues of perceptually overloading the target modality (Gori et al., 2016; Kristjánsson et al., 2016). Increasing pixel density of the outputted display does not always lead to a parallel improvement in perceptual ability (Grant et al., 2016, 2018), and increasing the volume of substituted information could even negatively impact perception within the targeted modality (Brown et al., 2014; Brown & Proulx, 2016). This has important implications when considering whether sensory substitution can be applied to sport and exercise, as sensory overload or reduced perceptual ability could hinder performance, or even cause injury. However, recently there have been successful advances using principles from sensory substitution to create devices that provide simpler, more accessible visual information to the user (Morrison et al., 2021; Porquis et al., 2018). Past research with existing SSDs has offered compelling results (Grant et al., 2018; Striem-Amit et al., 2012). The development of the BrainPort Vision Pro particularly lends itself well to the context of sport and exercise, as it is a stand-alone unit, with an integrated camera and offers a good temporal resolution. A previous iteration of the BrainPort has also been used specifically for the purpose of sport, in the form of a climbing aid for Erik Weihenmayer (Levy, 2008; Twilley, 2017). Suggestions for designing effective SSDs were also discussed. From past research, there were two main components that required consideration. The first was the idea that, to avoid information overload, it is crucial to understand perceptual limitations of the target modality for sensory substitution. Kristjánsson et al. (2016) suggested that the best way to do this, is to apply psychophysical methods to the target modality via sensory substitution. The second component for designing effective devices, was the importance of understanding the value of the information being translated. In context, evaluating barriers to exercise participation was assessed as potentially useful information when considering areas for implementing sensory substitution technology.

The empirical work of the thesis was presented in Chapters 1, 2, and 3. Chapter 1 tackled fundamental components of perception via the BrainPort, right down to investigating the basic axiom of, ‘which way is up?’. It used perceptually ambiguous stimuli to explore how participants adopted different perspectives through the BrainPort in a variant of the graphesthesia task (Arnold et al., 2016, 2017). The findings suggested that individual differences can play a considerable role in perspective taking with the BrainPort and highlighted the need for customisable non-visual interfaces. It also hinted that task-specific differences may affect perception with the BrainPort. Specifically, it demonstrated that people most often took a 'self-centred from below' perspective, that is, 'looking up' from below the tongue at the stimuli. Crucially, however, the results also showed that people flipped their adopted perspective in response to vertically directional arrowheads, generally taking a decentred perspective. This may be due to the way that the BrainPort flipped vertical information: An arrow pointing 'up' in the visual field would corresponded to an arrow on the tongue pointing behind the user. This concept was further explored in Chapter 2.

Chapter 2 applied a cueing paradigm to the surface of the tongue via the BrainPort, in an inquiry of reflexive spatial attention. An adaption of the Posner Cueing Paradigm, used by Spence and McGlone (2001), was applied to the tongue to examine exogenous attention. Additionally, it included a tip versus back component to attempt to quantify differences previously highlighted in perceptual ability at the back section of the tongue (Haggard & de Boer, 2014; Pamir et al., 2020). It also split participants into four between-subject groups to explore differences in cueing modality (tactile unimodal, and audio-tactile crossmodal, respectively), and further probe potential differences in the BrainPort's rotation of space by manipulating keyboard response button mappings. It observed that spatial localisation ability, in response to cued information, is generally poor at the back of the tongue, but can be improved by providing cued information crossmodally via sound. This potentially indicates that the tongue may not have clear access to the general mechanism of spatial attention found in other parts of the body (Spence & McGlone, 2001; Spence & Gallace, 2007). The study did not find any major differences for keyboard mapping, and, it is worth noting that the sample size was sub-optimal for between-subject comparisons, so future research is required to continue exploring the aspect of perception through a tongue interface. Critically, SSD designers should take efforts to prevent attentional overload on the surface of the tongue, particularly at the back, and ensure that devices have some customisation built in to allow for users to tailor the feedback to their perceptual preference.

Chapter 3 used a mixed methods approach to study access to exercise for people with visual impairments over the course of the Coronavirus-19 pandemic, compared to data collected prior to the onset of the UK lockdown. The results showed that prior to the pandemic barriers to exercise participation were generally high, with people citing reasons such as lack of specialised support, lack of transport, or lack of specialised facilities as major factors that hindered them exercising. At the onset of the UK lockdown, barriers to exercise participation further increased, as the guidance encouraged people to exercise alone, and this was not an option for many people with visual impairments. However, as the pandemic progressed, technological solutions were implemented, such as using exercise equipment at home, or taking part in online classes specifically tailored for people with visual impairments. These methods compounded on the tentative reopening of facilities, to reduce barriers below pre-pandemic levels. The results of Chapter 3 align with other similar result conducted during the pandemic, showing that the national lockdowns disproportionally affected people with disabilities and visual impairments. It also highlighted a willingness of people with visual impairments to adopt novel technological interventions to help improve exercise activities.

Finally, Chapter 4 built on the work of the previous chapters, and applied the knowledge generated to developing new prototype software, Climb-o-Vision, to help navigation in rock climbing. The software utilises existing open source, cost-effective hardware, and the program itself is also publicly available. However, in its present form, a potential user would have to have a basic understanding of initialising programs through the command line. Future iterations of the program will employ an accessible audio/graphical user interface that will be ported to a tablet or mobile, as these devices were reported to already be commonly used for exercise purposes in Chapter 3. According to Chapter 1, the concept of verticality on a tongue interface is somewhat problematic, with many users interpreting spatial information located to the top of the camera’s field of view differently on the tongue. Additionally, Chapter 2 demonstrated that attention on the back of the tongue is greatly inhibited compared to the tip of the tongue. For these two reasons, Climb-o-Vision crops the vertical axis to provide only a narrow band of vertical information (in practical terms, this translates to only displaying information that is level to where the user’s head is) and translates hold locations uniformly across the tongue to maximise signal strength. In essence, Climb-o-Vision provides only lateral cues to a climbing hold's location, leaving the user to determine vertical positioning using active sensing through head motion.

The primary goal of this thesis was to explore the efficacy of tongue interfaces for the purpose of improving access to exercise for people with blindness and visual impairments. The overall findings suggest that tongue interfaces that substitute an entire visual scene simultaneously, such as the BrainPort, may not be the best option as an exercise assistive device. Furthermore, as the BrainPort is 'hard-coded', it lacks flexibility to adapt to individual, or task-specific, differences. Additional findings suggest that access to exercise can be improved through the application of technology, specifically, throughout the Coronavirus-19 pandemic when exercise habits were severely disrupted. This bodes well for novel technological interventions. Finally, it demonstrates a conceptual application of these findings, to suggest one way in which tongue interfaces could viably be used to improve access to rock climbing. During the course of the research program, important knowledge was uncovered and disseminated concerning spatial attention on the surface of the tongue, further adding to current models of attention and spatial cognition, highlighting that general mechanisms of attention may not be easily applied to the tongue. Additionally, more barriers to exercise participation were explored, offering new compelling evidence on potential ways to improve exercise participation at a social and societal level.

This thesis sets up two parallel courses for future work, primarily, testing the efficacy of Climb-o-Vision on climbing performance, but also more widely, applying computer vision techniques to other SSDs. As previously stated, new iterations of the Climb-o-Vision device are in development which consequently will continue drawing on the main findings of this thesis, offering practical applications of the findings presented here.

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