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## Orientation of Tactile Attention on the Surface of the Tongue

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Data can be requested at:

[https://osf.io/qhbk7/?view\\_only=7238eb229417486faa3de6ad7c6e4a33](https://osf.io/qhbk7/?view_only=7238eb229417486faa3de6ad7c6e4a33)

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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 when solely provided via electrotactile feedback 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.

### Orientation of Tactile Attention on the Surface of the Tongue

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 adaptations of the Posner Cueing Task (Posner et al., 1984; Posner & Cohen, 1984), 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, 1984). 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 (Hiimae & 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 Volder, 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 generalizable to the tongue.

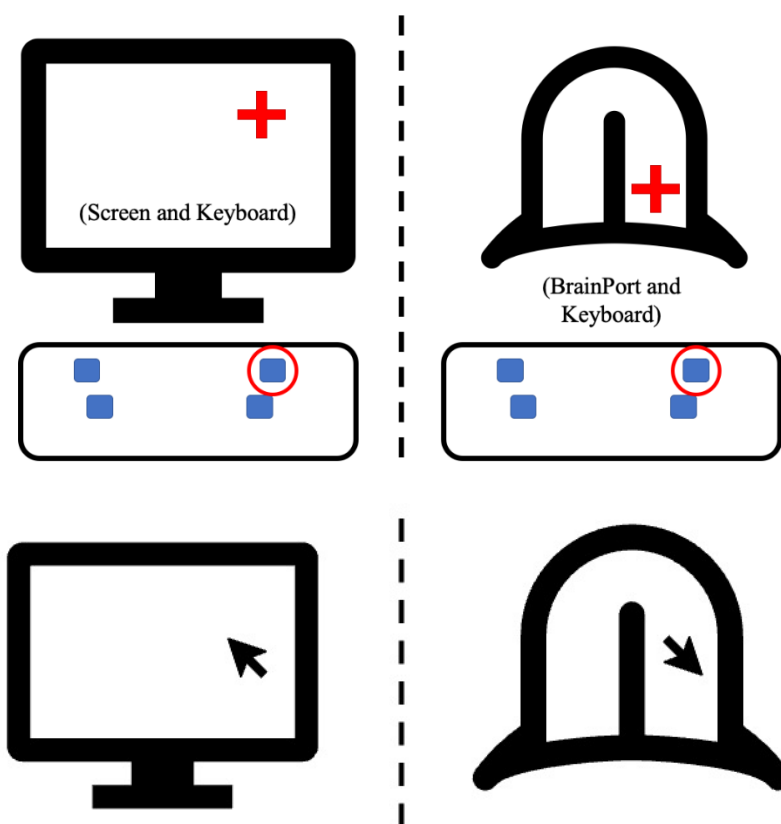
Although using foam cubes to deliver tactile information to the hands is a viable choice for examining tactile spatial construction, it is unfortunately not a feasible choice when studying the tongue. In contrast, the development of tongue interfaces from the field of sensory substitution may offer the 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, 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 organization 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 minimize 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 maximizing 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 prioritization 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 cognition. As the tongue does not have a uniform sensitivity across the surface, instead of using pure left versus 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 tongue also inhibits attention prioritization 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 hypothesized 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 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 hypothesized that mappings between the tongue and the keyboard would be more effective than mappings between the screen and the keyboard when using the BrainPort.

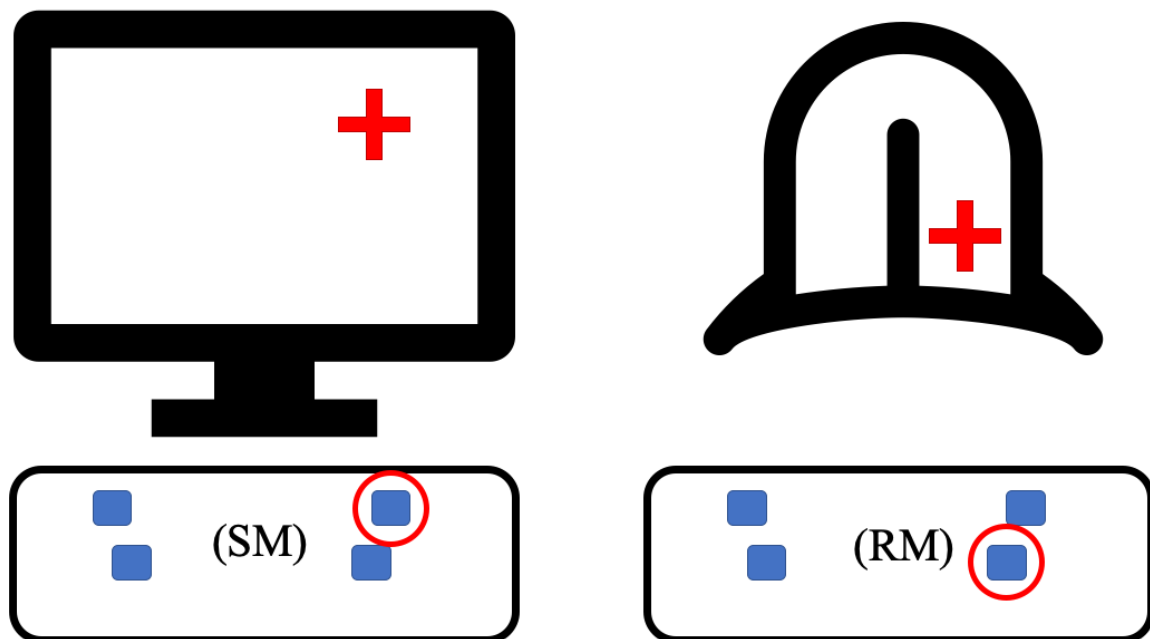
## **Methods**

### **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 position 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 condition, the response buttons position corresponded to the target position on the tongue, with information appearing at the top of 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 analyzed, 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 =  $24.1 \pm 4.3$  years; 15 female), and audio (mean age =  $20.7 \pm 1.3$  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 emphasize 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, 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 processor at the rear, and a 394-electrode array that forms the inter-oral display (IOD). The IOD is  $29.5 \times 33.8 \times 7$  mm in size, and the electrodes are spaced at 1.32 mm from center to center (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  $3^\circ$  and  $47^\circ$ , for this study, the FoV was set at  $47^\circ$  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 familiarize 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

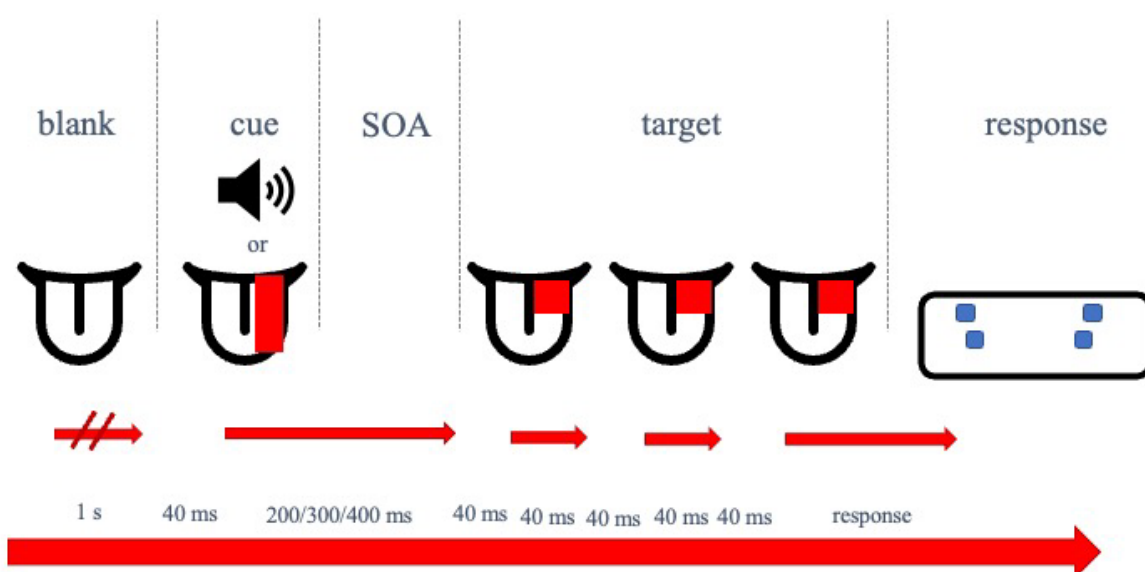


screen for the benefit of the researcher, so when the participant initially made tongue contact with the electrodes, they received some electrical feedback, but it was not overwhelming; as the BrainPort provides a truly novel experience, initial contact can be surprising. Once the participant was completely 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 familiarization. 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  $\times$  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 familiarize 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

randomized 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. 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 examining 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 verses audio cues), and keyboard mapping (reversed mapped verses 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 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 visualizations 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.*

	<i>F</i>	<i>df1</i>	<i>df2</i>	<i>p</i>	$\eta^2$
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 verses 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**

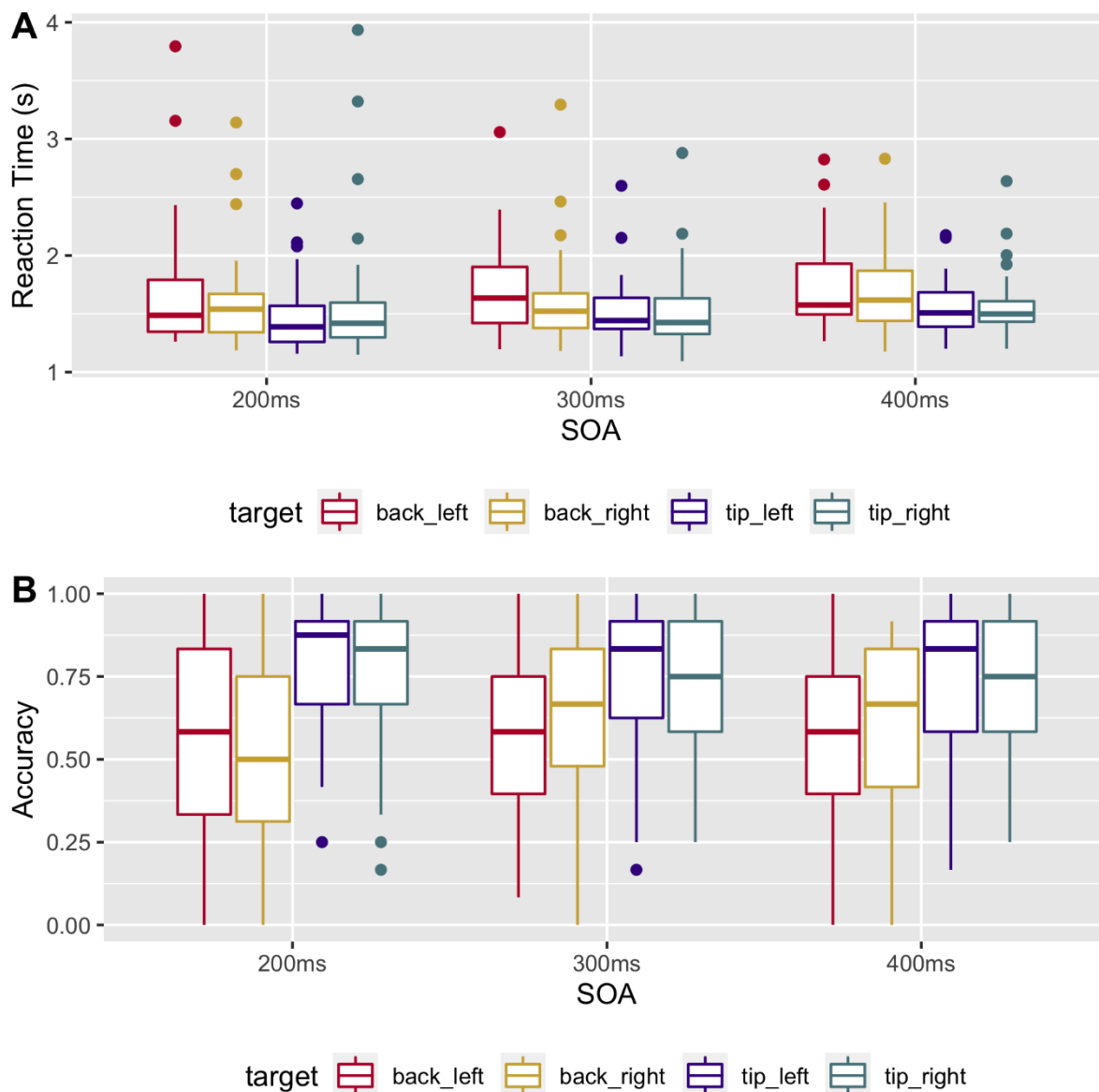
*ANOVA results for accuracy in the unimodal tactile condition.*

	<i>F</i>	<i>df1</i>	<i>df2</i>	<i>p</i>	$\eta^2$
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
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 25<sup>th</sup>, and 75<sup>th</sup> 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.*

	<i>F</i>	<i>df1</i>	<i>df2</i>	<i>p</i>	$\eta^2$
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 ( $.83 \pm .38$  proportion correct) trials being responded to more accurately than contralateral ( $.80 \pm .40$  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**

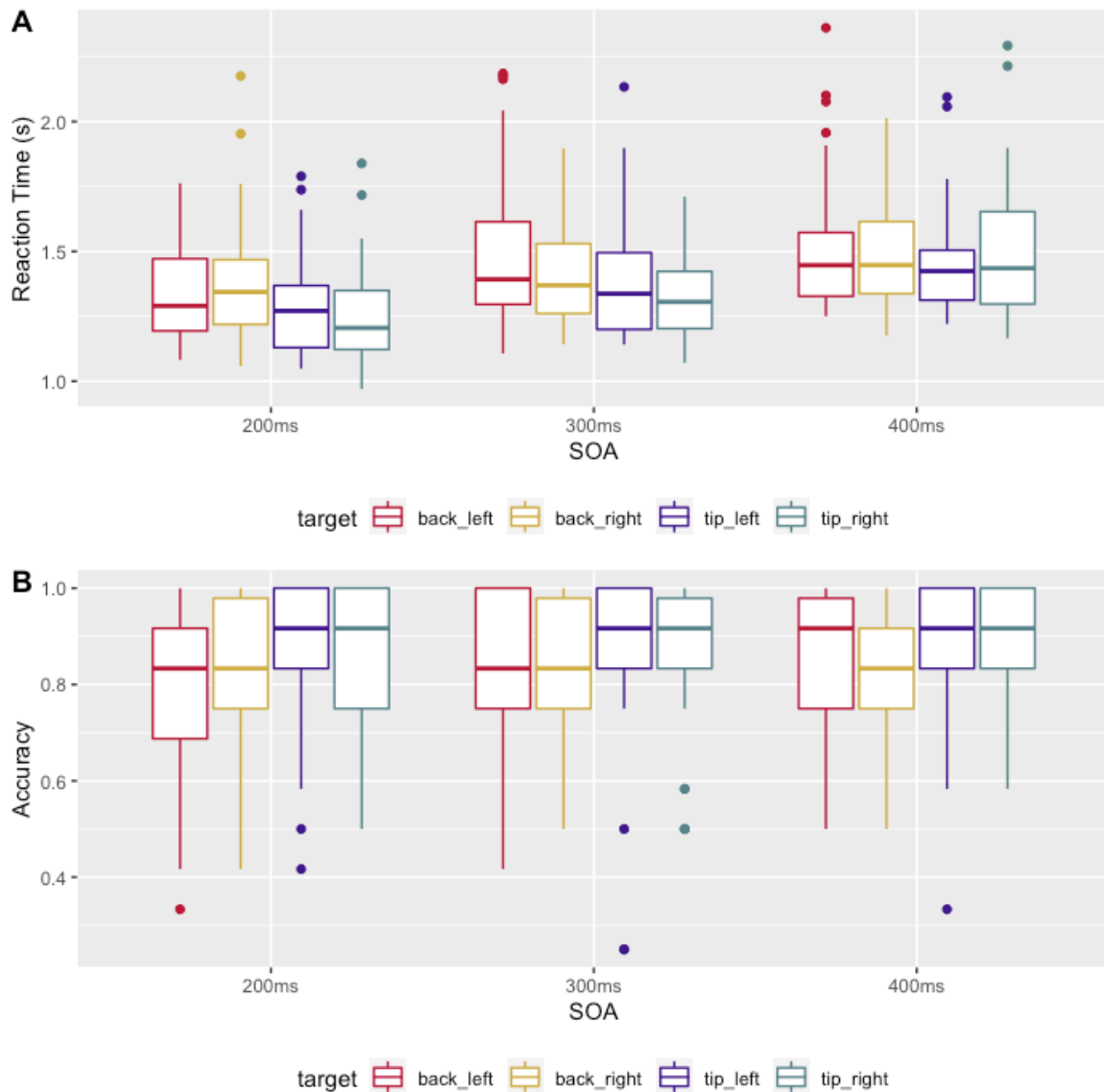
*ANOVA results for accuracy in the crossmodal auditory condition.*

	<i>F</i>	<i>df1</i>	<i>df2</i>	<i>p</i>	$\eta^2$
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 25<sup>th</sup>, and 75<sup>th</sup> 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

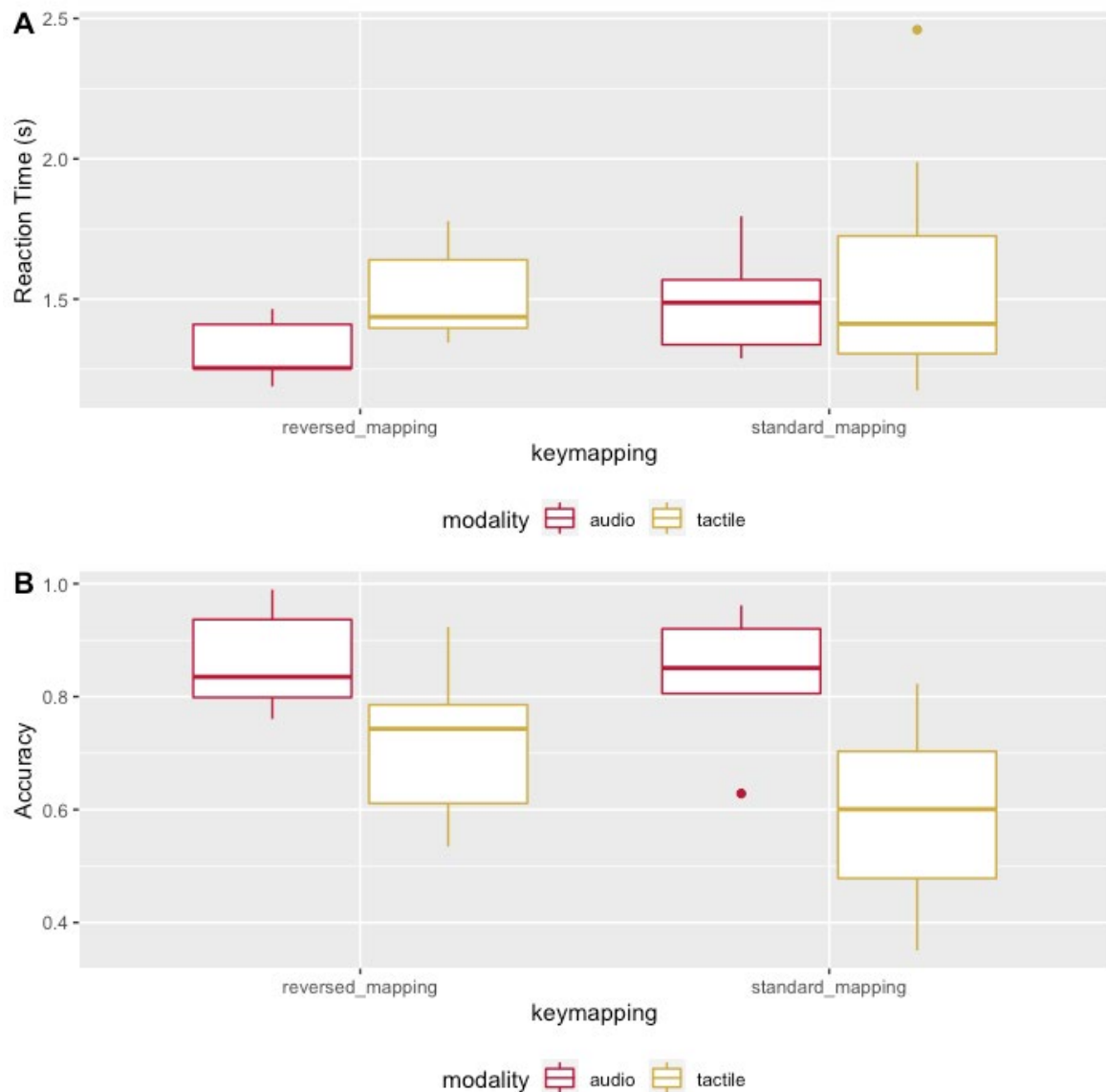
For RT, no significant effect was found for the factor of cueing modality ( $F(1, 35) = 3.05, p = .089, \eta^2 = .080$ ), keyboard mapping ( $F(1, 35) = 2.35, p = .134, \eta^2 = .063$ ), and

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<sup>th</sup>, and 75<sup>th</sup> 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 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 (Hiimae & 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 localization 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 generalizable 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 prioritize 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 vocalization as symbolically meaningful (Posner, 1980). Considering the role the tongue plays in speech production (Hiemae & 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 hypothesized 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 localization in the vertical plane, perhaps this is also the case for tactile localization 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, 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), 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; Simaeyts 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 localized 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 gradient 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 spatialized 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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