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Shape Discrimination Using the Tongue: Implications for a Visual-to-Tactile Sensory Substitution Device

Margaret Vincent, Hao Tang, Wai Khoo, Zhigang Zhu and Tony Ro *

The City College and Graduate Center of the City University of New York, 365 Fifth Ave.,
New York, NY 10016, USA

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Abstract

Sensory substitution devices have the potential to provide individuals with visual impairments with more information about their environments, which may help them recognize objects and achieve more independence in their daily lives. However, many of these devices may require extensive training and might be limited in the amount of information that they can convey. We tested the effectiveness and assessed some of the limitations of the BrainPort device, which provides stimulation through a 20 × 20 electrode grid array on the tongue. Across five experiments, including one with blind individuals, we found that subjects were unable to accurately discriminate between simple shapes as well as different line orientations that were briefly presented on the tongue, even after 300 trials of practice with the device. These experiments indicate that such a minimal training regimen with the BrainPort is not sufficient for object recognition, raising serious concerns about the usability of this device without extensive training.

Keywords

Vision, somatosensory, sensory substitution, visually impaired

1. Introduction

Sensory substitution devices (SSDs) have the potential to provide individuals with visual impairments with more information about their environments, which may help them recognize objects and achieve more independence in their daily lives. Two promising SSDs that have been developed are the vOICe and the BrainPort (Bach-y-Rita *et al.*, 1998; Meijer, 1992). The vOICe transforms visual information into an auditory soundscape, associating height to pitch and brightness with loudness (Meijer, 1992). In contrast, the BrainPort

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* To whom correspondence should be addressed. E-mail: tro@gc.cuny.edu

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system utilizes electrotactile stimulation to the tongue *via* a 20 × 20 electrode grid array to convey visual information captured with a small video camera mounted on a pair of sunglasses (Bach-y-Rita *et al.*, 1998). Users attempt to learn to interpret these patterns of stimulation as the shape, size, and location of objects in their environment, allowing them to better navigate their surroundings. Additionally, unlike the white cane and guide dog, the BrainPort device provides the potential ability to process some types of visual information and aid in the identification of objects. However, the BrainPort suffers from limitations, including the high cost (∼US$10 000), cumbersomeness, and its interference with basic functions such as talking and eating (Kendrick, 2009; Steeves and Harris, 2012). Furthermore, some have questioned whether somatosensory input can be utilized for shape discrimination and object identification because of several limitations (Spence, 2014), including the active/serial exploration typically required for object recognition through touch (Gibson, 1962) as well as the limited spatial resolution of the somatosensory system (for a review see Lederman and Klatzky, 2009).

Although the spatial acuity of the tongue is much lower than that of normal vision, the acuity of the tongue has been shown to be relatively high compared to other parts of the body given its high density of tactile mechanoreceptors (Myles and Binseel, 2007; Trulsson and Essick, 1997). Essick and colleagues measured the average threshold height for the recognition of embossed letters as 5.1 mm (Essick *et al.*, 1999), and Steele and colleagues found an age related reduction in lingual tactile acuity, with the average threshold measured as 5.55 mm in older participants (over 60) and 4.8 mm in younger participants (under 40) (Steele *et al.*, 2014). Van Boven and Johnson (1994) obtained psychophysical thresholds for tactile spatial resolution using grating orientations on the tongue and found that the finest gratings whose orientation were discriminated reliably had groove widths that averaged 0.58 mm on the tongue, compared to 0.51 mm and 0.94 mm for the lip and finger, respectively. Not only were these measurements highly reproducible between sessions, but an overall improvement of 2% per session was observed.

Additional studies utilizing electrotactile stimulation on the tongue support this learning effect. Sampaio and colleagues (2001) measured tactile acuity using a tongue display unit (TDU) composed of a 12 × 12 electrode array to present a Snellen E of varying sizes and orientations to the tongue. After nine hours of training, average acuity improved from 20/860 to 20/430. Ptito and colleagues (2005) trained users to discriminate the orientation of the letter T and found that after seven hours of training, performance improved from chance to approximately 90% and reaction time decreased from approximately 50 s to 20 s for sighted controls and 40 s to 5 s for blind participants. In a more recent study, Nau and colleagues (2013) also found a significant increase in acuity scores for gratings and a white Tumbling E on a black background after 15 hours of training with the BrainPort. However, acuity did not improve for other measures, such as a black Tumbling E on a white background or a rotating Landolt C (black on white, and *vice versa*).

Other studies using electrotactile stimulation of the tongue have shown that users are able to perceive and recognize simple geometric forms. For instance, Bach-y-Rita and colleagues (1998) found that participants were able to discriminate between circles, squares, and triangles that were presented to the tongue *via* a 49-point electrotactile array with 79.8% accuracy. In a later study, Ptito and colleagues (2012) trained users to recognize squares, triangles, rectangles, and the letter E using the TDU. After 150 min of training, discrimination accuracy improved from approximately 55% to 90%, and response time decreased from 10–15 s to 5–10 s. In an earlier study, participants completed seven hours of training to learn how to discriminate the direction of moving dots presented to the tongue *via* the TDU (Ptito *et al.*, 2009). Following training, blind and sighted participants were able to accurately detect motion with 95% and 90% accuracy, respectively. In a similar motion discrimination study, participants completed 150 min of training (Matteau *et al.*, 2010). Discrimination accuracy for moving dots improved from 55.1% and 54.8% for blind and sighted participants to 91% and 85.9%. In addition to movement and simple shape recognition, other studies have demonstrated that users are able to perceive and discriminate between different stimulation intensities (Lozano *et al.*, 2009), identify simple real world objects (Nau *et al.*, 2015), and point to and avoid obstacles in navigation courses (Chebat *et al.*, 2011). These previous studies indicate that extensive amounts of training and unnaturalistically long scanning times may be necessary for such TDUs to become moderately but not perfectly effective.

Although many studies using the BrainPort have permitted subjects to freely scan stimuli for relatively longer lengths of time (⩾one minute) (Chebat *et al.*, 2007; Nau *et al.*, 2013, 2015; Sampaio *et al.*, 2001), which may have improved performance, it may not necessarily be helpful for navigation or object recognition in real world situations where objects are rarely stationary. Furthermore, sighted people continuously and intentionally move their eyes and head to extract information from their environment, and unintentional microsaccades and small movements of the head make it very difficult to maintain a steady fixation on a single object for much longer than a few hundred milliseconds. Therefore, when using the BrainPort in the real world, it will likely be difficult to maintain steady positioning of the camera on an object without any shift in the activated pixels on the intra-oral device (IOD), even with a concerted effort. And although this type of motion from movements of the camera or objects in the environment could be argued to facilitate object recognition, the amount of noise that would be introduced from movements of the camera and/or objects might actually interfere with object recognition.

Given previous claims and findings that object recognition through somatosensory input may be very limited (Spence, 2014) and may require active, serial exploration (Gibson, 1962), we chose to systematically assess the ability of sighted (Experiments 1–4) and blind (Experiment 5) individuals to discriminate static stimuli delivered to the tongue through activation of specific electrodes on the TDU through a computer rather than a head-mounted camera. Previous studies that have allowed active sensing while using SSDs, in which subjects can actively scan and interact with the stimuli (Chebat *et al.*, 2007; Maidenbaum *et al.*, 2016), may have resulted in high levels of performance because of the longer durations of exposure to the stimuli as well as the active sensing itself. To control for the duration and extent of active sensing, we presented the stimuli in our experiments for a short duration. Specifically, in the first four experiments, the stimuli were delivered for a 500 ms duration to minimize scanning of the objects with the tongue and to better mimic the brief amount of time that users can maintain a steady enough gaze on an object without head movements that would shift the activated electrodes on the IOD. Additionally, the consistent onset and offset times of the stimuli minimize sensory adaptation effects and the variability that may be introduced by subjects using different exploratory strategies with longer presentation times. In Experiment 5, we also directly compared performance between briefly presented *vs.* continuously presented stimuli. Finally, we also compared whether increasing the surface area of the stimulation would improve performance by including filled as well as outlined shapes (Experiments 1 and 2), thicker *vs.* thinner lines (Experiment 4), and lines of varying orientations (Experiments 3 through 5). We used a large number of trials per condition in all experiments to increase their reliability.

To preface the results, Experiment 1 demonstrates that it is difficult to discriminate shape stimuli, regardless of whether the shapes are filled (low spatial frequency) or outlined (high spatial frequency). Experiment 2 indicates that practice does not improve shape discrimination performance. Experiment 3 suggests that line orientations that differ by 30 degree angles are easier to discriminate than shapes but still difficult to differentiate and that practice does not improve performance. Experiment 4 shows that performance is better for line orientations that differ by 45 degree angles (i.e., three different line orientations), with no improvement in performance from practice. Experiment 5 suggests that blind and sighted users perform similarly when discriminating electrotactile stimulation and that longer durations of stimulation do not necessarily improve performance.

2. Materials and Methods

2.1. Apparatus

We used the BrainPort TSP100 workstation (BrainPort, WICAB Inc., Wisconsin, USA), which is composed of an intra-oral device (IOD), user module, operator module, and a laptop computer. The workstation can deliver stimulation either directly through images captured by a camera or by images generated on the laptop computer. For the current studies, we presented stimuli that were generated on the laptop and did not use the camera. The IOD is a tongue array consisting of 400 circular electrodes arranged in a 20×20 matrix (Electrode Material: 316LVM stainless steel; Electrode Diameters: 0.762 mm; Electrode spacing: 1.32 mm center–center spacing; Overall IOD size: $29.5 \times 33.8 \times 7$ mm). The BrainPort workstation translates images into electrical pulses that are transmitted to the tongue *via* the IOD.

2.2. Protocol

All experiments took place in a sound-attenuated room, with participants seated in front of a laptop computer that was used to record the participants' responses. Participants were instructed to place the disinfected IOD on the anterior midsection of the dorsal surface of the tongue, close their mouth, and gently hold the wire of the IOD to ensure that placement stayed constant. Electrical stimulation (pulse amplitude) was increased in 0.2 V intervals, until a robust but comfortable level was reached. In order to obtain an optimal stimulation level for each participant that was not too uncomfortable, electrical stimulation was sometimes increased to a level that surpassed the appropriate level and was then decreased until a clearly detectable stimulation level was reached. Participants were then briefly introduced to the stimuli that were to be used in the experiment.

2.3. Participants

Table 1 provides detailed information on the participants and experiments. All participants were naïve to the BrainPort device and did not participate in other experiments. Each participant gave written informed consent and completed the experiment during a single session. The study was approved by the Institutional Review Board of the City University of New York.

3. Experiment 1

In Experiment 1, we assessed the participants' ability to discriminate between briefly (500 ms) presented circles and squares delivered to their tongue electrotactically. Twelve sighted undergraduate students took part in the experiment for partial or extra course credit.

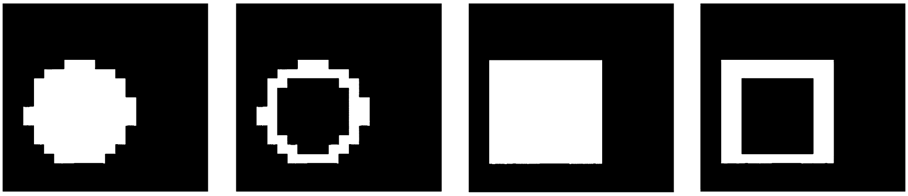
Table 1.
Participant details and summary of results

Experiment	Participants	Stimuli	Practice	Overall Mean Performance (%)	Chance Performance (%)
Experiment 1	sighted $N = 12$	squares & circles (filled & outline)	none	53.8	50.0
Experiment 2	sighted $N = 11$	squares & circles (filled & outline)	before	54.9	50.0
			after	57.7	
Experiment 3	sighted $N = 8$	30° lines (left diagonal, right diagonal, vertical, horizontal)	before	59.6	25.0
			after	57.4*	
Experiment 4	sighted $N = 14$	45° lines, thick & thin (left diagonal, right diagonal, vertical)	before	85.8*	33.3
			after	83.5*	
Experiment 5	blind $N = 4$	45° lines (left diagonal, right diagonal, vertical)	before	85.3*	33.3
			after	81.6*	

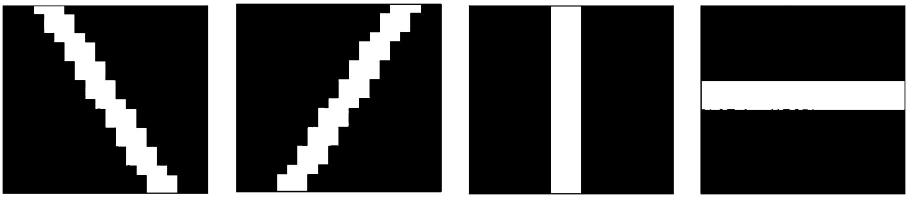
* $p < 0.05$.

3.1. Stimuli

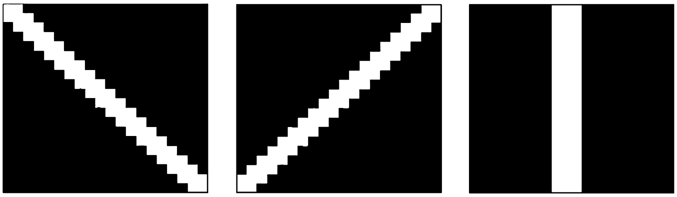
Four different stimuli were used to assess the discrimination abilities of the participants: filled circles (10 electrodes in diameter; ~70 total electrodes), filled squares (10 × 10 electrodes; 100 total electrodes), outline circles (10 electrodes in diameter with a two-electrode outline width; ~44 total electrodes), and outline squares (10 × 10 electrodes in height and width with a two-electrode outline width; 64 total electrodes) (see Fig. 1).



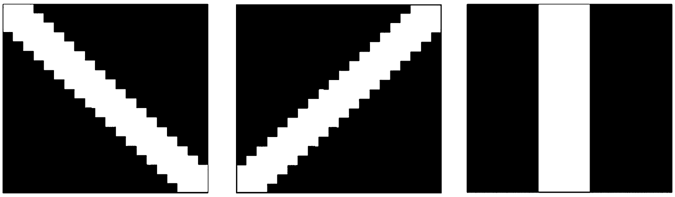
Experiment 1 & Experiment 2



Experiment 3



Experiment 4



Experiment 4 & Experiment 5

Figure 1. Stimuli for Experiments 1–5.

3.2. Task and Procedure

Experiment 1 consisted of 200 randomized trials, with each shape type presented 50 times. During each trial, a shape was presented to the tongue for 500 ms and participants were required to indicate whether they had felt a square or circle; subjects responded only to the shape, with filled/outline serving as an independent variable. The 500 ms presentation time minimized the ability of individuals to freely scan the stimuli. Responses were made using a laptop computer by clicking one of two buttons (circle or square) displayed on the screen. Because we were interested in shape discrimination accuracy rather than speed, participants were provided with unlimited time to respond after the brief stimulus presentation and were encouraged to guess if they were not sure which shape had been presented. Although the level of electrical stimulation for each participant was not recorded for this experiment, we used the same intensity setting procedure for Experiments 3, 4, and 5, which provided an average stimulation level of 4.80 V.

3.3. Results and Discussion

Mean performance for shape identification is shown in Fig. 2. A 2 × 2 ANOVA was conducted with outline type (filled *vs.* outline) and shape (circle *vs.* square) as the two within-subject factors. Overall discrimination accuracy, which was obtained by averaging the scores for all four stimulus types, was very poor ($M = 53.8\%$, SD = 10.1). The main effects of outline type ($F < 1$, $\eta^2 = 0.006$) and shape [$F(1, 11) = 2.06$, $p = 0.18$, $\eta^2 = 0.13$] were not significant, indicating that performance on the filled *vs.* the outline shapes and the

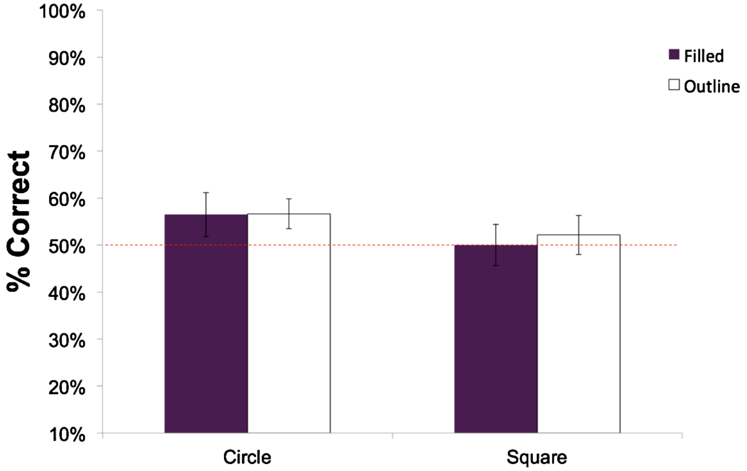


Figure 2. Discrimination performance in Experiment 1. Chance-level performance is indicated by the dashed horizontal line. Error bars are ±1 standard error of the mean.

squares *vs.* the circles was equally poor. The outline type and shape interaction was also not significant ($F < 1$, $\eta^2 = 0.004$).

After Bonferroni correction for multiple comparisons, discrimination accuracy was not significantly above chance for all stimulus types (all ts < 2.06, all ps > 0.05). Performance levels were suboptimal (<57% in all conditions). These results suggest that participants have a difficult time discriminating between shapes, regardless of whether they are filled or outline.

4. Experiment 2

To assess whether minimal levels of practice may improve performance, we incorporated practice trials in Experiment 2. Eleven sighted undergraduate students took part in the experiment for partial or extra course credit. Participants' ability to discriminate between circles and squares delivered to their tongue was assessed after 200 practice trials.

4.1. *Task and Procedure*

Experiment 2 was administered using the same equipment, stimuli, and methods as Experiment 1, except for the addition of practice trials. Participants first received 200 randomly ordered practice trials with feedback on the accuracy of the subject's shape response in the form of a display indicating the stimulus that was presented. This practice block took an average of 9.01 min to complete. After practice, 200 randomized experimental trials with no feedback were completed by each participant. Although the level of electrical stimulation for each participant was not recorded for this experiment, we used the same threshold procedure for Experiments 3, 4, and 5, which provided an average stimulation level of 4.80 V.

4.2. *Results and Discussion*

Mean performance during and after practice is shown in Fig. 3. A three-way ANOVA was conducted with practice (practice session with feedback *vs.* experimental session without feedback), outline type (filled *vs.* outline), and shape (square *vs.* circles) as the three within-subject factors. As in Experiment 1, overall performance, which reflects the combined average for all shape stimuli during both practice and experiment trials, was low (56.3%). Although performance slightly increased after the practice session with feedback from 54.9% (SD = 6.1) to 57.7% (SD = 13.8), the main effect of practice was not significant ($F < 1$). Unlike in Experiment 1, performance for outline shapes ($M = 58.1\%$, SD = 8.6) was significantly different than performance for filled shapes [$M = 54.5\%$, SD = 9.5; $F(1, 10) = 8.17$, $p = 0.02$, $\eta^2 = 0.06$]. The practice × outline type interaction was also significant [$F(1, 10) = 14.99$, $p = 0.003$, $\eta^2 = 0.06$] because performance was better for the outlined shapes

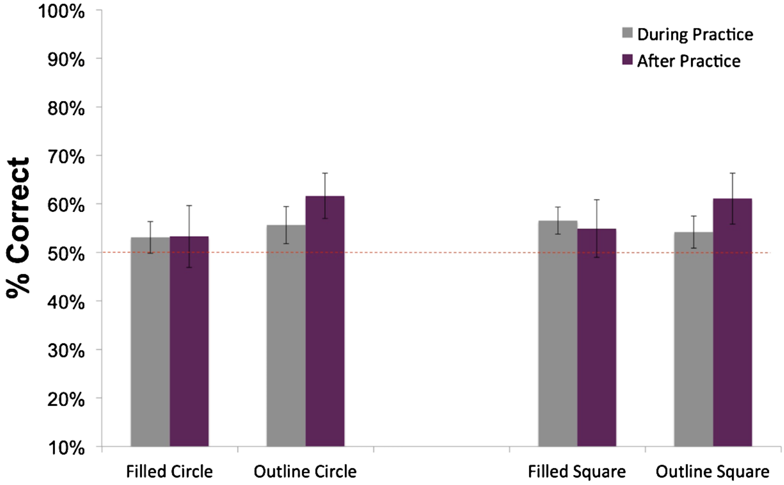


Figure 3. Discrimination accuracy in Experiment 2. Chance-level performance is indicated by the dashed horizontal line. Error bars are ±1 standard error of the mean.

after practice ($M = 61.3\%$, SD $= 12.9$) as compared to during practice ($M = 54.9\%$, SD $= 7.2$) but performance for filled shapes was similar during ($M = 54.8\%$, SD $= 5.6$) as compared to after practice ($M = 54.1\%$, SD $= 15.2$). None of the other main effects or interactions approached significance (all Fs < 1).

After Bonferroni correction for multiple comparisons, discrimination accuracy was not significantly above chance for all stimulus types during and after practice (all ts < 2.48, all ps > 0.05). These results suggest that a minimal level of practice does not improve shape discrimination performance for filled and outline shapes. Performance levels remained suboptimal ($<65\%$ in all conditions).

5. Experiment 3

In order to assess whether participants were capable of discriminating simpler stimuli, Experiment 3 examined whether participants were able to differentiate between different line orientations. Four types of stimuli were used: a left diagonal line that was 30 degrees from vertical (width of two electrodes; length of 23 electrodes), a right diagonal line that was 30 degrees from vertical (width of two electrodes; length of 23 electrodes), a vertical line (width of two electrodes; height of 20 electrodes), and a horizontal line (width of 20 electrodes; height of two electrodes).

5.1. Task and Procedure

Experiment 3 was administered on eight sighted undergraduate students (six females; mean age of 20.9) using the same equipment as for Experiments 1 and 2. Experiment 3 consisted of 400 randomized trials; a 200 trial practice block with feedback about line orientation discrimination accuracy, which took an average of 10.58 min to complete, followed by a 200 trial block with no feedback. Each stimulus was presented 100 times; 50 times during the feedback trials and 50 times during the no-feedback trials. During each trial, a line type was presented to the tongue for 500 ms and participants were required to indicate whether they had felt a left diagonal, right diagonal, vertical line, horizontal line, or ‘nothing’. The 500 ms presentation time minimized the ability of individuals to freely scan the stimuli. Responses were made using a laptop computer by clicking one of five buttons displayed on the screen. Participants were provided with unlimited time to respond and were encouraged to guess if they were not sure which line orientation had been presented. The average level of electrical stimulation was 4.44 V.

5.2. Results and Discussion

Mean performance during and after practice is shown in Fig. 4. A two-way within-subject ANOVA was conducted with practice (practice session with feedback *vs.* experimental session without feedback) and line orientation (left diagonal *vs.* right diagonal *vs.* horizontal *vs.* vertical) as the two within-subject factors. Overall performance, which reflects the combined average for all line

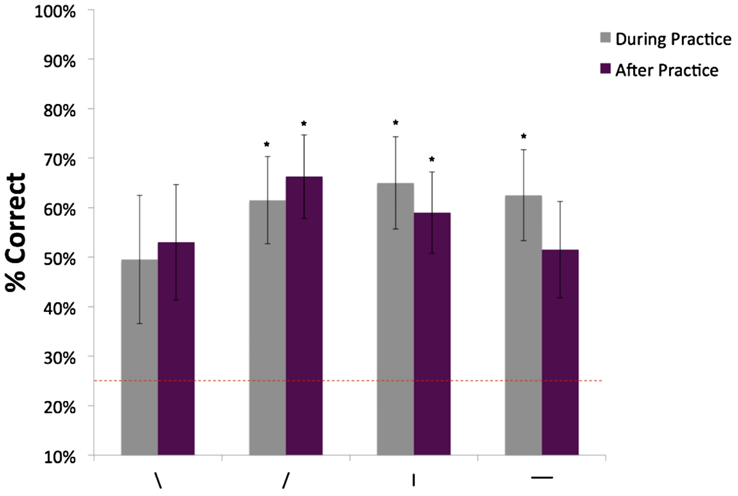


Figure 4. Discrimination accuracy in Experiment 3. Chance-level performance is indicated by the dashed horizontal line. Error bars are ±1 standard error of the mean. $^* p < 0.05$.

types during both practice and experiment trials, was better in this experiment than in the previous two experiments (58.5%, with chance performance at 25%). Performance slightly decreased after the practice session with feedback (from 59.6% to 57.4%), but this main effect of practice was not significant ($F < 1$, $\eta^2 = 0.01$). The main effect of line orientation was also not significant [$F(3, 21) = 1.40$, $p = 0.27$, $\eta^2 = 0.20$]. The practice × line orientation interaction was marginally significant [$F(3, 21) = 2.91$, $p = 0.059$, $\eta^2 = 0.089$].

After Bonferroni correction for multiple comparisons, overall discrimination accuracy, which reflects the combined average for all line types, was not significantly above chance during practice ($M = 59.6\%$, SD = 26.3; $t(7) = 3.71$, $p = 0.056$, two-tailed). Performance after practice, however, was significantly above chance ($M = 57.4\%$, SD = 23.3; $t(7) = 3.93$, $p = 0.048$, two-tailed). Overall discrimination accuracy during practice did not differ significantly from after practice [SD = 0.08; $t(7) = -0.768$, $p = 1$, two-tailed]. When comparing each line type against chance, performance during practice was significantly above chance for all of the line orientations (all ts > 4.08, all ps < 0.05, two-tailed) except for the left diagonal line [$t(7) = 1.89$, $p = 0.80$, two-tailed]. After practice, performance was significantly above chance for all line orientations (all ts > 4.12, all ps < 0.05) except for the left diagonal [$t(7) = 2.27$, $p = 0.376$, two-tailed] and horizontal line [$t(7) = 2.72$, $p = 0.240$]. When incorrect responses were made for the left diagonal line and right diagonal line, participants were more likely to report that it was a vertical line (55% and 56%, respectively). Additionally, when incorrect responses were made for the vertical line, participants were more likely to report that it was a right diagonal line (41%). Furthermore, when incorrect responses were made for the horizontal line, participants were more likely to report that they felt nothing (36%).

Although performance levels were statistically significant compared to chance performance in this experiment, these far from perfect (<70% accuracy) results suggest that it is nonetheless still challenging to differentiate between line orientations that are 30 degrees apart. We also found in this experiment that horizontal lines occasionally go undetected. Participants reporting that they felt nothing during the horizontal line condition supports prior evidence that tongue sensitivity decreases towards the back of the tongue (Wicab Inc., 2008). With the horizontal line, stimulation does not reach the more sensitive tip of the tongue as it does with the other line types, resulting in a weaker stimulation that may not be felt by the participant. This indicates that a substantial portion of the tongue and BrainPort IOD device may not be useful for discriminating shape information.

6. Experiment 4

To further assess the discrimination abilities of electrotactile stimuli on the tongue, Experiment 4 examined whether fourteen sighted undergraduate students (seven males, seven females; mean age = 19.4 years) were able to differentiate between vertical and diagonal lines that are 45 degrees apart. We incorporated two different widths for the line orientations to determine whether the width of the stimuli affects discrimination performance. Six types of stimuli were used: thin left diagonal line (width of three electrodes; length of 28 electrodes), thin right diagonal line (width of three electrodes; length of 28 electrodes), thin vertical line (width of three electrodes; length of 20 electrodes), thick left diagonal line (width of five electrodes; length of 28 electrodes), thick right diagonal line (width of five electrodes; length of 28 electrodes), and thick vertical line (width of five electrodes; length of 20 electrodes).

6.1. Task and Procedure

Experiment 4 was administered using the same equipment as for the previous experiments. Experiment 4 consisted of 600 randomized trials: a 300 practice trial block with feedback followed by a 300 trial block with no feedback. Each stimulus was presented 100 times; 50 times during the feedback trials and 50 times during the no-feedback trials. During each trial, a line type was presented on the tongue for 500 ms to minimize scanning of the stimuli and participants were required to indicate whether they had felt a left diagonal, right diagonal, or vertical line. Subjects responded only to the line orientation, with line thickness serving as an independent variable. Responses were made using a laptop computer by clicking one of three buttons indicating the line orientations displayed on the screen (left diagonal, right diagonal, or vertical). Participants were provided with unlimited time to respond and were encouraged to guess if they were not sure which line orientation had been presented. The average level of electrical stimulation was 4.84 V. Practice took an average of 10.42 min to complete.

6.2. Results and Discussion

Mean performance during and after practice is shown in Fig. 5. A three-way ANOVA was conducted with practice (practice session with feedback *vs.* experimental session without feedback), line thickness (thin *vs.* thick), and line orientation (left diagonal *vs.* right diagonal *vs.* vertical) as the three within-subject factors. Compared to the previous three experiments, overall performance, which reflects the combined average for all line stimuli during both practice and experiment trials, was relatively higher (84.6%). As in Experiment 3, performance slightly decreased after the practice session with

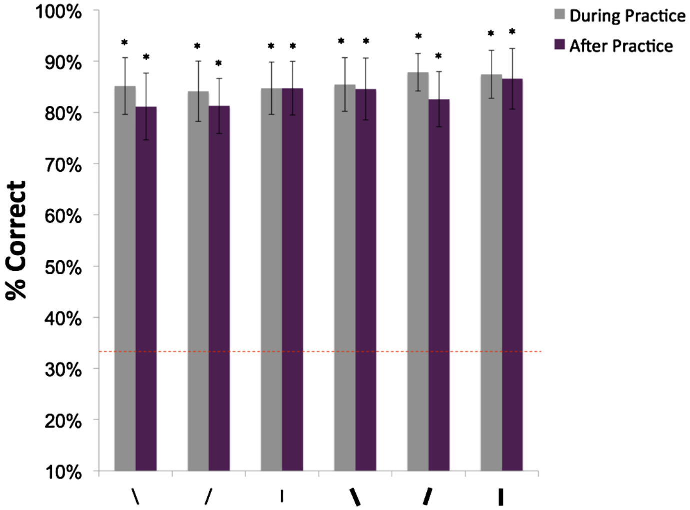


Figure 5. Discrimination accuracy in Experiment 4. Chance-level performance is indicated by the dashed horizontal line. Error bars are ±1 standard error of the mean. $^{*}p < 0.05$.

feedback from 85.8% (SD = 17.9) to 83.5% (SD = 20.9). This main effect of practice was marginally significant [$F(1, 13) = 3.27$, $p = 0.094$, $\eta^2 = 0.174$]. The main effect of line thickness was highly significant [$F(1, 13) = 9.64$, $p = 0.008$, $\eta^2 = 0.160$], with better discrimination performance for the thick lines ($M = 85.7\%$, SD = 18.6) as compared to the thin lines ($M = 83.5\%$, SD = 20.0). The main effect of line orientation and all of the interactions were not significant (all Fs < 1.3).

After Bonferroni correction for multiple comparisons, overall discrimination accuracy was significantly above chance for all of the conditions (all ts > 7.3, all ps < 0.05, two-tailed). These results indicate that participants are much better at discriminating vertical and diagonal lines that are 45 degrees apart than lines that are 30 degrees apart and that thicker lines improve discrimination performance. This experiment also provides further support that a minimal interval of practice does not improve performance. However, as in the previous experiment, overall levels of performance were still far from perfect (<85% accuracy).

7. Experiment 5

In this experiment, we tested blind individuals in a more ecologically valid task that used the same line stimuli as in Experiment 4 but required navigation in a virtual environment to assess whether their performance on somatosensory discrimination on the tongue may be better than that of normally sighted individuals. Cross modal interactions between touch and vision have been demonstrated in both normally sighted and blind individuals. Studies in sighted subjects have revealed that visual imagery is involved in tactile perception of object orientation (Sathian *et al.*, 1997), shape, and size (Klatzky *et al.*, 1987), and that activation of the visual cortex is associated with certain tactile tasks (Deibert *et al.*, 1999; Sathian *et al.*, 1997). Studies in blind individuals have revealed similar visual cortex activation during tactile discrimination tasks (Ptito *et al.*, 2005; Sadato *et al.*, 1996). Furthermore, a study comparing brain activity of blind and sighted individuals while participating in a tactile discrimination task revealed higher activity in the visual cortex and decreased activity in the secondary somatosensory cortex in the blind participants when compared to the sighted participants (Sadato *et al.*, 2002). These findings support cross modal plasticity in the blind and suggest that blind individuals not only recruit the visual cortex during tactile discrimination tasks but may possess a functional shift of the visual cortex from processing visual stimuli to processing tactile stimuli.

However, blindness-induced plasticity appears to differ considerably depending on the developmental period during which it occurs (Collignon *et al.*, 2013). Indeed, some studies have shown a critical period for cross modal plasticity in blind humans, which does not extend beyond the teen years (Cohen *et al.*, 1999; Sadato *et al.*, 2002; but see for dissenting research Burton *et al.*, 2002a, b; Sabbah *et al.*, 2016; Voss *et al.*, 2006). Additionally, studies have suggested that while congenitally blind and early acquired blind individuals demonstrate enhanced non-visual sensory perception, late blind individuals do not (Wan *et al.*, 2010a, b). As a proof of concept, we collected data from four blind subjects with varying ages of visual impairment to assess whether congenitally, early blind, and late blind individuals may benefit more from the BrainPort device than sighted individuals. Due to the restrictions and immobility of the BrainPort Workstation used in our studies, a virtual environment was utilized so that blind subjects could sit in front of a desk to navigate through the virtual environment (Khoo *et al.*, 2012, 2013, 2015).

7.1. Task and Procedure

Experiment 5 was administered on four blind adult subjects using the same equipment as for the previous experiments (see Table 2). Experiment 5 consisted of approximately 417 trials; 150 practice trials with feedback and an average of 267 experiment trials with no feedback. During the feedback practice trials, each stimulus was presented 50 times. Each line type was presented to the tongue for 500 ms to minimize scanning of the stimuli and participants were required to verbally indicate whether they had felt a left diagonal, right diagonal, or vertical line. Responses were recorded by the experimenter, who then provided verbal feedback indicating the correct response. Participants

Table 2.
Participant demographics for Experiment 5

Gender	Etiology
Female	Stardgardt disease, 8 years blind
Female	Retinitis pigmentosa, 20 years blind
Male	Retinopathy of prematurity, blind shortly after birth
Female	Leber congenital amaurosis, blind since birth

were encouraged to guess if they were not sure which line orientation had been presented. Practice took an average of 6.6 min to complete.

During the experimental trials, vertical and diagonal (that were 45 degrees from vertical) lines were presented to direct the subjects through a virtual environment. Line orientations were presented in accordance to the blueprint of the virtual environment and varied based on each participant's unique performance/location within the virtual environment. The experiment trials were delivered over the course of three separate blocks. The left diagonal line was presented an average of 111 times, the right diagonal line an average of 116 times, and the vertical line an average of 40 times. During each trial, a line type was presented to the tongue continuously until the subjects responded. To facilitate responding by blind participants, responses were made using a joystick. The average level of electrical stimulation was 5.10 V.

7.2. *Results and Discussion*

Mean performance during and after practice is shown in Fig. 6. After Bonferroni correction for multiple comparisons, discrimination accuracy during practice was significantly above chance for left diagonal and vertical lines (all ts > 6.78, all ps < 0.05, two-tailed), but not for the right diagonal line [$t(3) = 4.31$, $p = 0.138$, two-tailed]. Discrimination accuracy after practice was significantly above chance for right diagonal and vertical lines (all ts $>$ 9.95, all ps < 0.05, two-tailed), but not for the left diagonal line [$t(3) = 5.04$, $p = 0.09$, two-tailed]. A two-way within subjects ANOVA was conducted with practice (practice session with feedback *vs.* experimental session without feedback) and line orientation (left diagonal *vs.* right diagonal *vs.* vertical) as the two within-subject factors. Overall performance, which reflects the combined average for all line stimuli, slightly decreased after the practice session with feedback from 85.3% (SD $=$ 14.0) to 81.6% (SD $=$ 10.1), but this main effect of practice was not significant ($F < 1$). The main effect of line orientation and the practice × line orientation interaction were also not significant ($F < 1$). These results indicate that continuous stimulation does not yield performance differences as compared to a briefly presented stimulus.

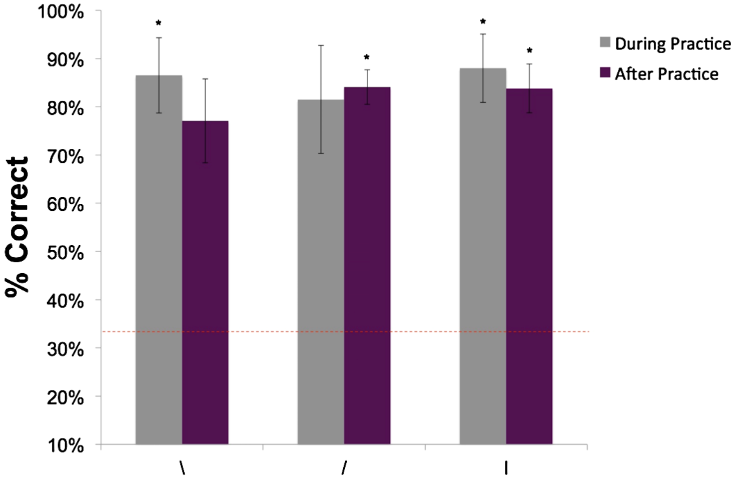


Figure 6. Discrimination accuracy in Experiment 5 for lines during practice with 500 ms stimulation and after practice with continuous stimulation. Chance-level performance is indicated by the dashed horizontal line. Error bars are ±1 standard error of the mean. $^{*}p < 0.05$.

Although the task and interface used in this experiment was different to those used in Experiment 4, we compared the performance between sighted and blind participants using a one-way between-subjects ANOVA to assess whether blind individuals might be better at using the BrainPort than sighted individuals. There was no significant difference between the groups during ($F < 1$) or after practice ($F < 1$). Performance did not significantly differ between groups for any of the line orientations (all Fs < 1).

These results indicate that the blind users performed similarly to the sighted users when discriminating line orientations. However, although these results show no difference between blind and sighted participants, the results must be interpreted with caution given the small sample size. Past studies utilizing larger sample sizes have documented superior performance in blind participants compared to sighted participants in various tactile discrimination tasks (Chebat *et al.*, 2011; Kupers *et al.*, 2010). Of note, the results from the study conducted by Kupers and others, which consisted of a route navigation and a route recognition task for which participants trained over four consecutive days, were mixed. Specifically, overall performance during training was not statistically different between the blind and the sighted. Similarly, when formally tested after training (day 5), both groups scored equally well. A significant difference between groups was only found when considering the results on the last day of training. Furthermore, while another study examining tactile acuity of the tongue with the TDU found that 30% of blind participants attained the highest possible visual acuity score compared with only 8.4% of the sighted controls (Chebat *et al.*, 2007), this subset of blind participants had previous experience with the TDU as they had participated in a prior study assessing motion discrimination with the tongue. As such, these results may be due to differences in the level of familiarization and training with the device rather than differences in vision.

Verbal feedback provided by Subject 1 following the experiment suggests that continuous stimulation may be more difficult to discriminate than brief periods of stimulation; the participant reported that she found that continuous stimulation of the stimuli made identification more challenging than when the stimuli were presented for 500 ms. Examination of the subject's performance supports this claim; her discrimination accuracy decreased after the practice session from 96.6% to 82.21%. This increased difficulty with continuous stimulation may be due to adaptation of the tongue sensory receptors and the lack of an offset sensory response. However, this observation cannot be generalized given the anecdotal nature of this comment from one subject.

8. Fatigue and Learning Effects

To assess whether participants exhibited either fatigue or a learning curve during each of the five experiments, we compared overall performance during the first half of each experiment to the second half of each experiment. During Experiment 4, average performance during the experiment trials decreased slightly from 85.6% (SD = 20.8) to 82.1% (SD = 21.2), which may reflect fatigue. This difference in performance was significant [$t(13) = 3.11$, $p = 0.016$, two-tailed, Bonferroni corrected]. There were no statistically significant differences in performance during any of the other experiments (all ts < 2.09, all ps > 0.15) (see Supplementary Table S1).

9. General Discussion

Five experiments examined the ability of sighted and blind subjects to discriminate electrotactile stimuli briefly presented to the tongue (see Table 1). Experiment 1 demonstrates that it is difficult to discriminate shape stimuli, regardless of whether the shapes are filled in or only outlines. Additionally, Experiment 2 indicates that a practice block of 200 trials with accuracy feedback minimally improves performance (from 54% to 61% accuracy). Experiment 3 demonstrates that vertical and diagonal lines that are 30 degrees apart are distinguishable but nonetheless still difficult to discriminate and that horizontal lines occasionally go undetected by the user. Experiment 4 demonstrates that it is possible to discriminate between vertical and diagonal lines that are 45 degrees apart and that performance is better for thicker lines. Finally, Experiment 5 preliminarily suggests that discrimination accuracy is similar for blind and sighted subjects and that continuous stimulation does not improve performance, but a larger sample size, a more direct comparison between continuous and burst stimulation, and comparisons of individuals with low vision are necessary in order to confirm these claims.

Overall, participants were unable to discriminate between stimuli with a reasonable level of accuracy, and decent but far from perfect levels of performance were limited to very simple stimuli in the form of three line orientations. Additionally, for better performance levels, stimuli need to be localized to the tip of the tongue, due to the decrease in sensitivity of the mid-to-back portion of the tongue (see Experiment 3). These far from perfect levels of performance, even with the simplest of shapes, suggest that the BrainPort device may not be a very effective sensory substitution device unless more practice and training are provided to the users and the stimuli are localized to the more sensitive (e.g., tip) region(s) of the tongue.

The results of our study are generally inconsistent with previous studies utilizing electrotactile stimulation of the tongue for shape recognition. For instance, Ptito and colleagues (2012) revealed superior performance levels for shape discrimination using the TDU both at baseline and after training, compared to our study that used similar stimuli (Experiment 2). Specifically, performance at baseline was approximately 55%, with chance performance of 25% compared to our baseline performance of 54.9% with chance performance of 50%. Additionally, performance in their study significantly improved following training to approximately 90%, whereas performance in our study only improved to 57.7% following practice. The discrepancy between our findings and those in their study is likely related to several differences in study design. For one, participants in their study were provided a maximum of 30 s to identify each stimulus, which permitted participants to scan the stimuli with their tongue; our study utilized a much briefer presentation time of 500 ms that prevented scanning of the stimuli. Secondly, participants were provided significantly more training in their study; participants in their study received 150 hours of training stretched over four consecutive days, compared to our study which provided an average of 9.01 min of practice during a single session. Additionally, participants in their study were either blind or blindfolded sighted controls, whereas our study only utilized sighted participants who were not blindfolded. Lastly, it can be argued that their study utilized stimuli that were more easily discriminated (triangle, square, rectangle, and the letter E), whereas our study utilized just two shapes that were spatially more similar (square *vs.* circle), especially given the pixelation of the shapes from the limited resolution 20 × 20 IOD. However, in our Experiment 4, which utilized line stimuli that were more discriminable, performance improved to 84% after practice, which is not much worse than the 90% performance levels found in their study.

Our research joins others that demonstrate that naïve BrainPort users typically do not perform significantly above chance during discrimination tasks. For instance, a recent study assessing object identification and word recognition found that participants were unable to complete the tasks at baseline (Nau *et al.*, 2015). However, after approximately 15–20 hours of training, the participants were able to complete the tasks with moderate success (i.e., correctly identify objects an average of 15 of 20 trials, and read an average of 1.5 of 10 words). Similarly, a study assessing light perception, light localization, temporal resolution, motion detection, and grating and visual acuity found that participants performed at chance level for all tasks at baseline, with performance significantly improving for 4 of 11 tasks after 15 hours of training (Nau *et al.*, 2013). While these papers demonstrate significantly improved performance following training, the current results suggest that performance levels necessary for object recognition in real world situations may not be adequate and may require extensive training.

Studies utilizing auditory SSDs also demonstrate the importance of training with these devices. For instance, a study using sounds that simulated those made by The Prosthesis for Substitution of Vision by Audition (PSVA) found significant improvements in the detection of elements and patterns (bars and dots that were translated into sounds according to a pixel-to-frequency code) after two hours of practice (Poirier *et al.*, 2006). Specifically, performance improved from 67% to 94% accuracy for elements and 36% to 78% for patterns. Another study assessed the ability to detect basic shapes and color information using a different visual-to-auditory sensory substitution device called EyeMusic, which conveys visual information using musical notes on a pentatonic scale generated using a sweep-line technique where each image is processed column-by-column from left to right constructing a ‘soundscape’ (Abboud *et al.*, 2014). After 2–3 hours of training with the device, sighted and blind participants performed well (74.7–91.5%). However, given the variability in participant performance, it was suggested that more training was likely needed for some participants who found the device less intuitive and as such did not perform as well. Two individuals who have used the vOICe extensively over a period of years demonstrate the possible benefits of extensive practice with the device, as they have been able to acquire some practical everyday life skills and advanced visual functions, such as depth perception (Ward and Meijer, 2010). Given the promise of both auditory and tactile sensory substitution devices following training, studies comparing the effectiveness of these two forms of SSDs would be informative.

Despite several studies demonstrating improved performance with SSDs, it has become increasingly clear that most SSDs are not intuitive to use and thus require extensive training in order for users to interpret novel input correctly (Maidenbaum *et al.*, 2014). Indeed, recent reports have stressed the importance of developing training protocols to improve the usability of SSDs (Maidenbaum *et al.*, 2014; Nau *et al.*, 2015). However, even with longer training protocols, performance levels are far from perfect. For example, after many hours of training and after 12 months of BrainPort use, word identification performance improved to only around 50% accuracy and four-object identification performance was between 80% and 90% and never reached 100% accuracy (Nau *et al.*, 2015). On the other hand, several recent studies have demonstrated that the vOICe (Brown *et al.*, 2015; Stiles and Shimojo, 2015) and EyeMusic (Maidenbaum *et al.*, 2016), two different auditory SSDs, are intuitive to use, with high levels of performance after minimal or short training. Stiles and Shimojo (2015) found that naïve participants were able to match vOICe sounds to images just as well as intensively trained participants. Similarly, Brown and colleagues (2015) demonstrated that naïve users of the vOICe can discriminate certain sonified lines easily, performing above chance without training. Furthermore, blindfolded sighted users were able to navigate virtual environments and find doors, differentiate between them based on their features and surroundings, and walk through them with an 89–95% success rate after minimal training (<20 min) with the EyeMusic SSD (Maidenbaum *et al.*, 2016).

Our results demonstrate low levels of performance that suggest that the BrainPort is not easy or intuitive to use. However, it is important to summarize the limitations of our study. For one, our practice consisted of only 150–300 trials over a period of 6.60–10.57 min, which may not be enough to improve performance. Similarly, we tested only one stimulus presentation duration of 500 ms, so it is unclear if performance may have been better with a longer presentation time (e.g., 1 s or more) that may have allowed for improved performance by allowing sufficient time for active tactile exploration (Gibson, 1962). Given the better performance observed in studies that allowed active exploration of stimuli during longer periods of time (Bach-y-Rita *et al.*, 1998; Matteau *et al.*, 2010; Ptito *et al.*, 2012), it is possible that discrimination accuracy in our experiments would have been higher with longer stimuli durations. Indeed, given our finding that the back portion of the tongue is less sensitive than the tip, longer stimulation that allows for exploration using the tip of the tongue may be necessary to successfully use the BrainPort for object recognition. Although we did not parametrically test the effectiveness of different stimulus delivery times, our comparisons indicate that a brief period of stimulation (i.e., 500 ms) may allow for better performance than continuous stimulation (Experiment 5) and suggest that stimuli that have onsets and offsets may prevent adaptation and allow for better discriminability. Furthermore, studies have suggested that active tactile exploration may not improve performance as compared to passive tactile stimulation (Lamb, 1983; Vega-Bermudez *et al.*, 1991). Future studies using more levels of training duration and stimulus presentation times, as well as comparisons between active *vs.* passive exploration of the tactile stimulation, may clarify the optimal parameters for using this device.

Unlike most previous studies with the BrainPort, our study mostly tested sighted individuals who were not blindfolded, as the experiments required them to use their eyesight to make responses during the tasks. This issue may have significant effects on the results of our studies, as people often find it easier to mentally imagine a visual object with their eyes closed (Spanos and Stam, 1979). Additionally, research has revealed that during imagery of visual objects, auditory and somatosensory cortices show a clear deactivation, which may be a consequence of filtering out irrelevant stimuli to obtain image saliency (Amedi *et al.*, 2005). Similarly, Azulay and colleagues (2009) found deactivation of the auditory and visual areas in sighted individuals, and deactivation of the auditory cortex in blind individuals, during memory retrieval of abstract words. These results suggest that deactivations of sensory cortices that are irrelevant to a specific task may be helpful in the retrieval of intrinsically stored information by reducing noisy synaptic input from less relevant brain areas and that this non-relevant cortical deactivation may be needed for perception. Indeed, a neuroimaging study comparing blind and blindfolded sighted users of the TDU revealed significant deactivation of the visual cortex in the sighted participants during an orientation discrimination task, suggestive of increased attentional resources directed towards the somatosensory input (Ptito *et al.*, 2005).

A study that assessed the effect of visual deprivation on Braille training found that normally sighted individuals who were blindfolded for five consecutive days performed better than those who were not blindfolded, independent of Braille training (Kauffman *et al.*, 2002). Thus, the sighted participants in our study may have performed better had they been blindfolded, allowing interference from irrelevant visual stimuli to be reduced. Similarly, results may have been different had we used blind participants in all of our studies, as past studies have suggested that blind users outperform sighted users in tasks utilizing electrotactile stimulation of the tongue (Chebat *et al.*, 2011; Kupers *et al.*, 2010). However, our results suggest that, at least with shape discrimination from tongue stimulation, sighted and visually impaired individuals perform similarly, which is consistent with many other studies of electrotactile stimulation of the tongue (Lee *et al.*, 2014; Matteau *et al.*, 2010; Ptito *et al.*, 2005, 2009, 2012; Sampaio *et al.*, 2001).

Although performance was similar between those with normal vision as compared to those with visual impairments, our results may have more direct implications for those with late acquired blindness considering their sensory perception is similar to that of sighted users, as compared to those with congenital blindness who may have undergone more extensive cross modal plasticity (Sadato *et al.*, 1996, 2002). However, our results with a congenitally blind user may suggest otherwise (see Experiment 5), which is consistent with the finding that early blind (blind for 10 or more years) and late blind (blind less than 10 years) performed similarly across 11 computer-based psychophysical tests with the BrainPort (Nau *et al.*, 2013).

10. Conclusion

Based on these results, we conclude that the BrainPort is extremely challenging to use when stimuli are presented in short 500 ms bursts, as well as with continuous stimulation, and that minimal training (e.g., 300 trials) does not adequately prepare users to successfully use the device for object recognition. Additionally, our findings suggest that the back of the tongue is likely not sensitive enough to accurately detect and discriminate stimuli. Thus, better performance may require brief stimuli to be presented to the tip portion of the tongue or for stimuli to be presented for longer periods of time to allow exploration with the tip of the tongue, which may be why past studies with longer periods of stimulation demonstrate better discrimination performance than ours (Matteau *et al.*, 2010; Ptito *et al.*, 2005, 2009, 2012). Previous findings that training can improve discrimination response times (Ptito *et al.*, 2005, 2012) are promising, as BrainPort users may be able to improve their speed of discrimination to the point that they can rapidly detect objects presented to the IOD. Our research also joins others that demonstrate that naïve users typically do not perform significantly above chance performance (Nau *et al.*, 2013, 2015). However, while these papers, as well as others (Matteau *et al.*, 2010; Ptito *et al.*, 2005, 2012; Sampaio *et al.*, 2001), demonstrate improved performance following training, it is clear that users still do not perform at a level that is necessary for object identification in real world situations, which raises concerns about the usability of the BrainPort device without extensive training.

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