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Visual-to-auditory sensory substitution alters language asymmetry in both sighted novices and experienced visually impaired users

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Abstract

Visual-to-auditory sensory substitution devices (SSDs) provide improved access to the visual environment for the visually impaired by converting images into auditory information. Research is lacking on the mechanisms involved in processing data that is perceived through one sensory modality, but directly associated with a source in a different sensory modality. This is important because SSDs that use auditory displays could involve binaural presentation requiring both ear canals, or monaural presentation requiring only one – but which ear would be ideal? SSDs may be similar to reading, as an image (printed word) is converted into sound (when read aloud). Reading, and language more generally, are typically lateralised to the left cerebral hemisphere. Yet, unlike symbolic written language, SSDs convert images to sound based on visuospatial properties, with the right cerebral hemisphere potentially having a role in processing such visuospatial data. Here we investigated whether there is a hemispheric bias in the processing of visual-to-auditory sensory substitution information and whether that varies as a function of experience and visual ability. We assessed the lateralization of auditory processing with two tests: a standard dichotic listening test and a novel dichotic listening test created using the auditory information produced by an SSD, The vOICe. Participants were tested either in the lab or online with the same stimuli. We did not find a hemispheric bias in the processing of visual-to-auditory information in visually impaired, experienced vOICe users. Further, we did not find any difference between visually impaired, experienced vOICe users and sighted novices in the hemispheric lateralization of visual-to-auditory information processing. Although standard dichotic listening is lateralised to the left hemisphere, the auditory processing of images in SSDs is bilateral, possibly due to the increased influence of right hemisphere processing. Auditory SSDs might therefore be equally effective with presentation to either ear if a monaural, rather than binaural, presentation were necessary.

Introduction

A person’s ability to coherently perceive the world around them requires an acute understanding of many types of stimuli. However, the absence of a sensory modality (e.g., sight in visual impairments) limits access to the full richness of the external world. In a world mostly designed by the sighted for visual perception, visual impairment has a negative impact on many aspects of the lives of estimated 252 million visually impaired individuals (Bourne et al., 2017), such as decreased employability (Cavenaugh & Giesen, 2012; Goertz, van Lierop, Houkes, & Nijhuis, 2010) and increased likelihood of experiencing accidents such as falls (Ivers, Cumming, Mitchell, & Attebo, 1998) and suffering from anxiety or depression (Langelaan et al., 2007).

Yet there are techniques that enable the translation of one type of sensory information (e.g., sight) into another format (e.g., hearing or touch) for the sensory impaired (Bach-y-Rita & Kercel, 2003; Ghazanfar & Schroeder, 2006; Kim & Zatorre, 2008). One such technique is to adapt sensory processing via sensory substitution, implemented in sensory substitution devices (SSDs). SSDs are a form of assistive technology used to help compensate for missing sensory input by translating the information to a format to be processed by a functioning sensory system (Gregory, 2003; Renier & De Volder, 2010). These are generally made of three components: an input device (e.g., a camera to capture visual information), specialised software to convert the information from the input device into a different format and an output device (e.g., headphones or a tactile unit). SSDs aim to mitigate some of the challenges caused by visual impairment by providing improved access to the visual environment via alternate sensory information (Hara, 2015; Michael J Proulx et al., 2016; Sigalov, Maidenbaum, & Amedi, 2016; Striem-Amit, Bubic, & Amedi, 2012). Although SSDs have been studied in terms of their effectiveness, the ergonomics of their use has been neglected. Here we will review the different types of devices, their effectiveness, and perform a study of the fundamental neural basis for auditory processing with one to inform the ergonomics of its use.

There are two main types of SSDs that convert visual information to either (i) tactile or (ii) auditory information. Visual-to-tactile SSDs have been studied extensively using various sites of stimulation such as the back, fingers and the tongue (Bach-y-Rita & Kercel, 2003), with the latter in particular identified an effective location due to its high sensitivity and mobility and therefore used in the commercially-available BrainPort by Wicab (Bach-y-Rita, Kaczmarek, Tyler, & Garcia-Lara, 1998; Sampaio, Maris, & Bachy-y-Rita, 2001). In studies using the BrainPort, both blind and blindfolded sighted participants successfully performed simple object and shape recognition (Ptito, Moesgaard, Gjedde, & Kupers, 2005), orientation and mobility (Chebat, Schneider, Kupers, & Ptito, 2011), and word and letter recognition tasks (Nau, Pintar, Arnoldussen, & Fisher, 2015). However, from an ergonomic perspective, visual-to-tactile SSDs in general have limited resolution and acuity in comparison to other visual-to-auditory SSDs (Brown & Proulx, 2016) and have been found to cause irritation at point of stimulation (Auvray & Myin, 2009).

Visual-to-auditory SSDs, on the other hand, are cheaper, less intrusive, and afford higher resolution than visual-to-tactile SSDs (Brown & Proulx, 2016), suggesting that they may be particularly beneficial for the visually impaired. One example of a visual-to-auditory SSD, and also the one used in the present study, is The vOICe (Meijer, 1992). This free-to-download software captures visual information via a standard webcam, breaks the image down to roughly 4000 greyscale pixels, and converts each pixel to an auditory signal using the following principles. First, pixel luminance is coded to auditory amplitude with brighter pixels eliciting louder sounds. Second, vertical pixel position is coded to auditory frequency (500-5000Hz) with higher pixel elevation generating logarithmically higher pitched auditory tones. Third, horizontal pixel position is coded to both stereo pan and a temporal scan: the device scans from the left to the right across the visual field with pixels to the left being heard early in the scan and to the left side of the stereo auditory field. The auditory signal corresponding to the entire captured visual field is updated at the set scan rate (1 second by default), and is known as a soundscape. These soundscapes are relayed back to the user in real time via standard or bone conduction headphones.

Research using The vOICe has addressed the question of how well people can learn to ‘see’ through the soundscapes. Auvray, Hanneton and O’Regan (2007) demonstrated that novice, blindfolded participants were able to localise, recognise and discriminate between objects after an extensive 3-hour device-led training session. Pollok et al. (2005) found similar competency in users trained over a 3-week period; Proulx and colleagues demonstrated that participants could learn to use the device by active use at home, and formal training was not required (Michael J. Proulx, Stoerig, Ludowig, & Knoll, 2008). Ward and Meijer (2010) even found that long-term late (non-congenital) blind users of The vOICe reported to be able to ‘see’ with considerable detail while using the device due to visual memory evoked imagery

While such research demonstrates that even naïve users of SSDs can learn to recognise and localise objects, avoid obstacles and navigate in complex environments with minimal training, and long-term visually impaired users can indeed reconstruct percepts with considerable detail, much is still unknown about the neural mechanisms of how information during sensory substitution is processed and reconstructed into different formats. One uninvestigated area of research is hemispheric lateralization and how it can be applied to improve the current status quo for the users of visual-to-auditory SSDs. For example, The vOICe users need to attend to the soundscapes via stereo headphones using both ears. This is not practical in everyday situations where ambient sounds are the major source of environmental awareness to those with visual impairments. It might be possible to process mono soundscapes equally or at least sufficiently effectively using just one ear (Brown & Proulx, 2013). To our knowledge, it is not known whether users can effectively use visual-to-auditory sensory substitution in one ear, and whether a hemispheric lateralization bias might suggest that one ear rather than the other might be optimal for such use. This is crucial for the ergonomics of using this class of sensory substitution devices given that the mode of auditory presentation can influence optimal performance for the user. With our particular focus on hemispheric lateralization, we are examining the *neuroergonomics* of the use of the device in particular. That is, we are taking under consideration the combination of brain function and user performance to evaluate the use of sensory substitution to represent images with an auditory display. By taking the “neuroergonomics approach" (Parasuraman, Christensen, & Grafton, 2012), we would use such understanding of the underlying cognitive characteristics of sensory substitution with respect to hemispheric lateralization to develop more useable and accessible devices for the end user.

Hemispheric lateralization refers to the extent to which one side of the brain is dominant in processing particular information. Broadly, the right hemisphere of the human brain is associated with left-hand control and visual spatial perception; the left hemisphere is associated with right-hand control and language comprehension (Gainotti, Caltagirone, Miceli, & Masullo, 1981; Hugdahl & Westerhausen, 2015). The human visual system is an exemplary case of such lateralization of sensory and perceptual function as visual field information is represented contralaterally (in the opposite hemisphere). In the auditory system, the split in function is less clear though as both hemispheres receive information from each ear with some auditory processes shared across hemispheres (Doreen Kimura, 1967; Zatorre, 1989). Previous research has found that the left hemisphere is dominant in speech processing (Alho et al., 1998; Doreen Kimura, 1967), potentially due to its dominant role in processing information with high temporal precision (Belin et al., 1998). The right hemisphere, on the other hand, is dominant in the processing of music (Shankweiler, 1966). However, hemispheric lateralization is not consistent across all language-related cognitive functions (Noffsinger, 1985), even in the same sample of participants (Jäncke, Steinmetz, & Volkmann, 1992). While many functions are preferentially processed in the left hemisphere, such as Morse code (Jäncke et al., 1992; Papcun, Krashen, Terbeek, Remington, & Harshman, 1974), nonsense syllables (Doreen Kimura, 1967), and backward speech (D. Kimura & Folb, 1968). In contrast bilateral processing has been reported for non-melodic hums (Van Lancker & Fromkin, 1973), vowels (S. E. Blumstein, Tartter, Michel, Hirsch, & Leiter, 1977) and Turkish whistling (Güntürkün, Güntürkün, & Hahn, 2015); in both cases this is thought to be due to the physical properties of the acoustic inputs which rely upon processing in the right hemisphere. Table 1 provides a summary of some key examples of right hemisphere, left hemisphere and bilateral phenomena. Although there is some neuroimaging evidence suggesting some bilaterality in the representation of language (Van der Haegen, Westerhausen, Hugdahl, & Brysbaert, 2013), the evidence of a right ear advantage in language processing has been reported in several studies (for a review see Hugdahl & Westerhausen, 2015), and thus is highly reliable. Given the neuroergonimcs application in this article, and the behavioural measure of an ear advantage as an indication of laterality, the neuroimaging findings are not necessarily a concern here.

Further, there is also research suggesting that hemispheric lateralization is not uniform in everyone. For example, the right hemisphere dominance of speech processing is lower in left-handed people and in auditory disorders (Knecht et al., 2000; Pujol, Deus, Losilla, & Capdevila, 1999; Zurif & Bryden, 1969). Furthermore, evidence suggests that hemispheric lateralization can change for some tasks with the acquisition of new skills or training. Franklin and colleagues (2008) found that 46 month-old toddlers with knowledge of colour terms demonstrated a strong left-hemispheric bias in a colour perception task, compared to a strong right-hemispheric bias in 32 month-old toddlers still learning to use colour terms, suggesting that hemispheric lateralization changed with the acquisition of colour terms. Additionally, Bever & Chiarello (1974) found that hemispheric bias for recognizing simple melodies differs for musically experienced and musically naïve participants, with the former demonstrating a left hemisphere bias and the latter a right hemisphere bias. Finally, Larsen and Håkonsen (1983) found that congenitally blind children do not exhibit the typical left hemisphere bias for speech, suggesting that hemispheric lateralization can differ between visually impaired and sighted people.

How would visual linguistic information, such as letters, turned into sound with sensory substitution be processed in the brain? Even though there is extensive evidence that experienced users can use so-called “visual” areas, such as the visual word form area, to process images of words turned into sound with sensory substitution (Striem-Amit, Cohen, Dehaene, & Amedi, 2012), clearly there is a role for auditory processing to provide the initial perceptual code. Might there be hemispheric laterality for visual linguistic information perceived through sensory substitution? The examples in Table 1 were selected to illustrate the three possibilities for sensory substitution: left hemisphere, right hemisphere or bilateral.

First consider the case for left hemispheric lateralization. Bach-y-Rita and Kercel argued that reading braille and even reading in general may be forms of sensory substitution, suggesting a possible link between sensory substitution and language (Bach-y-Rita & Kercel, 2003; Deroy & Auvray, 2012). This might imply a similar left hemispheric lateralization bias observed in language processing during sensory substitution whether due to the linguistic content (Doreen Kimura, 1967) being presented when turning images of letters or words into something that can be touched or heard in sensory substitution. Visual-to-auditory sensory substitution might also rely on left hemispheric lateralization due to the nature of the auditory display, whereby pitch (perceived frequency) represents a dimension of space; the use of tones for linguistic decision making is also left lateralised (Zurif, 1974) and devices such as The vOICe use the same frequency range as human speech, and thus a similar use of tone (pitch) might require the same neural processing (Meijer, 1992).

Second, consider the case for right hemispheric lateralization. There is also evidence suggesting that the processing of visual-to-auditory sensory substitution may be more similar to music processing. Haigh and colleagues (2013), for example, found a positive correlation between musical training and acuity using The vOICe. This may in part be because both cognitive functions involve pitch processing (Peretz & Zatorre, 2005), and research suggests that pitch processing improves with musical expertise (Besson, Schon, Moreno, Santos, & Magne, 2007; Schon, Magne, & Besson, 2004). Furthermore, users of the visual-to-auditory SSD 'Eye-music' (Abboud, Hanassy, Levy-Tzedek, Maidenbaum, & Amedi, 2014), which uses timbre and musical notes to substitute for colours in addition to the conversion algorithm of The vOICe, could successfully decipher information about shape and colour together. This might imply a similar right hemispheric lateralization might exist for sensory substitution as it does for the processing of melodies (Doreen Kimura, 1964) and complex pitch perception (Sidtis, 1982) as noted in Table 1.

Third, consider also the case for bilateral processing of information. The processing of nonmelodic hums (Van Lancker & Fromkin, 1973) do not exhibit an advantage for either ear, and thus are bilaterally processed. Although EyeMusic provides an arguably more melodic version of sensory substitution than The vOICe, both are bound by the visual features in the image and thus might be better described as nonmelodic. Other research has found that a particular form of language that uses whistling in Turkey is surprisingly bilateral (Güntürkün et al., 2015). Even though the whistling encodes linguistic information and could arguably be considered melodic, the complex pitch perception involved places high demands on the right hemisphere with a resulting bilateral profile. This is certainly also the case with The vOICe and its use of pitch to encode the vertical dimension of images, so the processing of linguistic information might be similarly demanding of both hemispheres.

Here we assessed hemispheric lateralization in order to study the neural mechanisms involved in sensory substitution. A direct approach to test for hemispheric lateralization in visual-to-auditory sensory substitution would shed light on to the hemispheric processing of SSDs and, with the neuroergonomics approach guide the development of SSDs. We assessed the hemispheric lateralization of standard dichotic listening in both sighted and visually impaired participants as there are few studies of whether impaired vision impacts the lateralization of auditory language processing (Larsen & Hakonsen, 1983), and we assessed handedness. To investigate lateralization, we used the standard dichotic listening test (DLT), whereby participants are presented with two sounds simultaneously in each ear and asked to state which sounds they heard more clearly. The DLT is a reliable method for measuring the hemispheric lateralization of auditory processes (Asbjørnsen et al., 2000; S. Blumstein, Goodglass, & Tartter, 1975). A group of visually impaired, experienced vOICe users and a group of sighted, novice participants completed two DLTs, both adapted from the DLT used in the Bergen fMRI group's iDichotic app, which has been shown to be both quick and reliable in measuring hemispheric lateralization of speech processing (Bless et al., 2013). The first task was a DLT using spoken syllables and the second used basic stimuli produced by The vOICe (vOICe-DLT). We also asked participants to complete a handedness questionnaire to examine whether there is an association between handedness and hemispheric lateralization of visual-to-auditory sensory substitution as is seen with the processing of speech.

We sought to investigate whether or not there is a difference between hemispheric lateralization from the processing of spoken syllables and syllables sonified from their visual symbols to soundscapes using The vOICe. To do this, we conducted two experiments. Experiment 1 investigated hemispheric lateralization in novice (non-experienced) users of The vOICe. To add to the reliability and robustness of these results, and the ecological validity of considering this in the context of visual impairment, we performed a replication and extension with new stimuli in Experiment 2, which assessed whether hemispheric lateralization patterns differ between sighted participants using The vOICe for the first time versus blind experienced vOICe users.

Experiment 1 Methods

Participants

In Experiment 1, there were 12 adult sighted participants (6 females, 6 males, ages 19-43), all of whom were non-experienced (novice) users of The vOICe. The participants were recruited among undergraduate and postgraduate students and staff at University of Bath and Bath Spa University. Each participant gave written consent before participating in the study. Whilst the hearing abilities of each of the participants was not explicitly checked, there was verbal confirmation in the participant recruitment phase that the participants were not hearing impaired or using a hearing aid.

Materials

The handedness questionnaire was 10-items (Veale, 2014) adapted from the original 20-item Handedness Questionnaire from the Edinburgh Handedness Inventory (EHI) (Oldfield, 1971). The EHI asks questions such as whether the participant uses their right or left hand for various tasks such as writing, drawing, throwing, and using a toothbrush or spoon.

In Experiment 1 (DLT) 6 syllables were used -- /ba/, /da/, /ga/, /ka/, /pa/, /ta/ -- as presented in the iDichotic app (Bless et al., 2013) run on an iPad mini, with transmission via noise-cancelling headphones. Stimuli for vOICe-DLT was a set of 20 sound clips, each comprising two different vOICe soundscapes of capital letters from a selection of six. For Experiment 1 the strategy was to optimise the presentation of letters to aid in discrimination using The vOICe. The 6 letters (with differing capitalisation as indicated) were chosen in a pilot-testing phase based on differentiability: E, k, O, q, R, and S. All were rotated 90 degrees to the left as this resulted in more distinct soundscapes for the letters. Each soundscape was created by sonifying a white image on a black background, for maximum contrast, using the vOICe image sonification feature set on 1 second scan speed, normal contrast. The clips were edited using Audacity (http://audacity.sourceforge.net/) processed as in the DLT (see the Procedure) but instead using the soundscapes, such that the soundscapes were matched in the same way as the spoken syllables. In Experiment 1, the vOICeDLT stimuli were presented via headphones for the auditory component (hearing the soundscapes), and on a sheet of printed paper for the visual component (viewing the letters).

Procedure

The DLT stimuli were presented in iDichotic using the standard procedure in the app, as follows. This began with a basic learning phase that is included within the app that teaches the participant how to use it. Then there was the iDichotic listening test phase, during which participants had to choose which syllable they heard over the headphones from a choice of the six syllables they read on the iPad, and responses were recorded by the app. For each clip, audio of two different syllables were presented, with one panned 100% to the left ear and the other panned 100% to the right ear, with the signal amplitude normalized. The stimuli were presented in a total of 36 pairs each presented once, including all 30 possible pairs of different letters, plus 6 homonym pairs with the same syllable presented to the left and right ears, in a pseudo-randomized order.

For the second phase, participants were presented with the vOICeDLT stimuli, beginning with a 15 minute learning phase during which the participants were instructed to learn to differentiate between the novel sounds to their best of their ability, by listening to the sounds, and then informally testing themselves on their ability to match the soundscapes to the images of letters on the sheet of paper. This was followed by the vOICeDLT experiment, during which participants were presented a sound and pointed to the letter the sound is associated with, for each of the 30 pairs of different letters, presented in the same order for all participants as a single audio track. Syllables are used in the standard DLT as consonants are otherwise not easily spoken. Single letters were used with The vOICe due to the ability to present consonants without vowels, the length of presentation, and to avoid increasing cognitive load by presenting additional information that would be unnecessary for the task.

Laterality Index

Scores of hemispheric lateralization were calculated for both the DLT and vOICeDLT using Studdert–Kennedy and Shankweiler's (1970) laterality index (LI). This is calculated as LI = (R-L) / (R+L), whereby R is the number of stimuli directed to the right ear that were correctly identified, and L is the number of stimuli directed to the left ear that were correctly identified. Scores were therefore between -1 and 1 whereby a score of -1 suggests a strong right hemisphere bias, a score of 1 suggests a strong left hemisphere bias, and a score of 0 suggests no bias.

Scores for handedness were calculated using an index adapted from Oldfield (1971) using 10 questions as opposed to the original 20. The index is also calculated using the same formula (R-L) / (R+L). Preferences were scored as 'always right' (R=2), 'always left' (L=2), 'mainly right' (R=1), 'mainly left' (L=1), or 'no preference' (R=0, L=0). A score of -1 suggests strong left-handedness, a score of 1 suggests strong right-handedness and a score of 0 suggests ambidexterity.

Results

Participants in Experiment 1 were found to include both left handed (n=2) and right handed (n=10) individuals, with mean handedness scores of -80 and 88.5 respectively.

The DLT and vOICeDLT results are illustrated in Figure 1. To assess laterality in each condition, the DLT and vOICeDLT scores were each compared to zero. The DLT score was significantly different than zero, The vOICeDLT was also significantly different than zero, $t(11) = 2.3$, $p = .04$. In a comparison between LI scores, a t-test on the DLT versus the vOICeDLT found a greater LI for the DLT of 0.48 (0.09) compared to the vOICeDLT of 0.14 (0.05), $t\ (11) = 3.44$, $p = .006$.There were no significant correlations between handedness, vOICeDLT or DLT (*r*s ranged from .06 to .13, $p > .5$).

Experiment 2

Methods

Participants

Participants comprised of two groups: novice users of The vOICe who did not participate in the first experiment, and "experienced" visually impaired users of The vOICe. Note that The vOICe has not yet gained widespread daily usage, and thus the number of experienced, visually impaired users is limited making a larger number of participants unavailable. These participants already used the vOICe pragmatically, rather than acquiring experience through long-term recruitment and training as part of an experiment, thus making for an ecologically relevant comparison. The experienced group consisted of three male and two female participants, with their details provided in Table 2; a blind participant was excluded for not reporting the cause or duration of visual impairment (n = 5; mean age = 41 years, SD = 14.8). Participants were recruited from a forum used by both The vOICe users and researchers in the field. The novice group consisted of undergraduate students at the University of Bath (n = 15; mean age = 21.13 years, SD = 1.41). Each participant gave written consent before participating in the study. Whilst the hearing abilities of each of the participants was not explicitly checked, there was verbal confirmation in the participant recruitment phase that the participants were not hearing impaired or using a hearing aid. Indeed because of the auditory display used by The vOICe, no known users have hearing impairments as this would render the device difficult to use.

Materials

In Experiment 2, similar stimuli to those in Experiment 1 were presented, but instead incorporated into a fully-integrated online format. Participants gave consent and completed the handedness questionnaire as in Experiment 1, although within the online format. The same iDichotic task was utilised: 6 syllables were used as in Experiment 1-- /ba/, /da/, /ga/, /ka/, /pa/, /ta/, but adaptations were required in order for presentation within the online form. The audio for the syllables was taken from Sound of Text (http://soundoftext.com), and edited in Audacity. For each clip, audio files of two different syllables were opened with one panned 100% to the left ear and the other panned 100% to the right ear. Signal amplitude across stimuli was then normalized. The syllables were matched so that no combination of syllables, in terms of both the syllables themselves and their audio panning was used twice. That is, a pair of syllables could be used twice only if their panning was reversed. Each syllable was used six or seven times, and no one syllable was panned to one ear more than four or less than three times.

Stimuli for vOICeDLT was a set of 20 sound clips, each comprising two different vOICe soundscapes of capital letters from a selection of six— A, E, K, Q, R, S. These letters were chosen due to their distinct visual appearances, as in Experiment 1, but in this experiment they were presented for consistency with standard reading practice and applied use rather than discriminability. Unlike in Experiment 1, these were all capitalized and presented upright to test whether the results from Experiment 1 would generalise to the standard, canonical orientation of letters.

The training session consisted of two parts, both administered via online survey the first consisted of information on the basic rules of image-to-sound conversion and provided example vOICe soundscapes of basic shapes to introduce the participant to the conversion algorithm. The second introduced the soundscapes of the letters A, E, K, Q, R and S, and gave the participant a chance to try to match each soundscape with the correct visual presentation of the letter. Soundscapes were created using The vOICe as in Experiment 1.

Procedure

Experienced group

The experienced group completed the study via an online experiment, made accessible through screen readers, in which the handedness questionnaire, DLT and vOICeDLT were presented. First, participants were provided with information regarding the nature of the study before answering questions related to their visual impairment and their use of the vOICe. They then completed the handedness questionnaire. Next, they were asked to put on their headphones, and clarify they were on correctly (i.e., left headphone – left ear) before starting either DLT or vOICeDLT, the order of which was randomised across participants.

For each clip, participants were presented with the list of possible syllables (DLT) or soundscapes (vOICeDLT), and asked to select the syllable or soundscape that they could hear. If they could make out both sounds, they were asked to select the sound they heard more clearly. After the vOICeDLT test, participants were asked to confirm whether they heard clip only once. Finally, the experiment ended with a debriefing that explained the purpose of the research.

Novice group

The novice group also completed the study via an online experiment, but instead, in a lab with an experimenter present. However, to keep their experience as similar as possible to that of the experienced group, the experimenter was mainly silent and only answered basic questions before and after the experimental trials. The procedure was the same as for the experienced group, aside from the questions regarding visual impairment. They were instead asked to confirm that they were indeed naïve to The vOICe. Furthermore, between the DLT and vOICeDLT the novice group completed the training session introducing them to The vOICe and the soundscapes that would be used in vOICeDLT.

Experiment 2 Results

Participants in Experiment 2 were all right handed, with only three not obtaining a score of 1 on the handedness test, and there was no significant different between the experienced and novice groups (mean = .97, SD = .07 in the experienced group; mean = .97, SD = .08 in the novice group), $t(19) = 0.09$, $p = .93$. To test for normality, we used the Shapiro-Wilk test, as this is the most suitable test for small sample sizes (Yazici & Yolacan, 2007). This was found to not be significant for both the experienced and novice group categories and for the left, right and no hemispheric bias categories, suggesting that the normality assumption had been met. Levene's test was used to test for homogeneity of variances, as this is a robust test (Levene, 1960). This was found to not be significant too, *F*(5, 14) = 2.37, *p* = .09, suggesting that the homogeneity of variances assumptions was met.

Concerning the DLT, the average dichotic listening scores for syllables were similar for both experienced (mean = .30, SD = .39) and novice groups (mean = .28, SD = .32), as shown in Figure 2. This is indicative of a left hemisphere bias. One-sample t-tests found that the mean DLT score was significantly different from zero in the novice group, *t*(14) = 3.31, *p* = .005 (95% CI [9.7,45.4]), but not in the experienced group, *t*(4) = 1.74, *p* = .16 (95% CI [-4.1,82.7]).

Regarding vOICeDLT, novice participants had on average a greater number of correct responses than the experienced participants (10.3 and 7.4 respectively); an independent-samples t-test found this to be significant, *t*(16.1) = -2.55, *p* = .02. The laterality index results are plotted in Figure 3. The average scores on vOICeDLT both indicated a slight left hemisphere bias but this was smaller for the novice group (mean = .03, SD = .17) than for the experienced group (mean = .24, SD = .29), as shown in Figure 3. One-sample t-tests found that the mean vOICeDLT score was not significantly different to zero in either the experienced group, *t*(4) = 1.84, *p* = .14, nor the novice group, *t*(14) = 0.73, *p* = .48, and the groups were not significantly different, *t*(19) = 1.87, *p* = .08. Thus these results suggest that rather than left hemisphere bias, there is a bilateral bias for the vOICeDLT.

We then used a two-way repeated measures ANOVA to examine the effects of group and hemispheric lateralization of speech on vOICeDLT scores. The scores on the DLT were converted into a categorical variable defined by three categories, which were left hemisphere bias for scores that were greater than zero, right hemisphere bias for scores that were less than zero and no bias for scores that were equal to zero. Handedness scores were removed from the analysis as there were no left handed or ambidextrous participants, and there were only three participants with handedness scores of less than 1.

The results from the ANOVA showed that neither group, *F*(1, 14) = 3.29, *p* = .09, nor hemispheric lateralization of speech, *F*(2, 14) = 1.14, *p* = .35, had a significant main effect;nor was there a significant interaction between group and hemispheric lateralization of speech, *F*(2, 14) = .85, *p* = .45. There were no significant correlations between handedness, vOICeDLT or DLT (*r*s ranged from .07 to .20, *p* > .3).

Discussion

Our study found that spoken syllables, as tested by the DLT, are processed preferentially in the left hemisphere, in both sighted and blind participants. However, the processing of visual letters converted to sound showed bilateral hemispheric processing but neither sighted nor blind experienced participants demonstrated a lateralization bias. Thus, the bilateral processing of vOICe stimuli may be due to additional recruitment of the right hemisphere in processing acoustic stimuli, as has been proposed for vowels and Turkish whistling (S. E. Blumstein et al., 1977; Güntürkün et al., 2015).

The similarities between the two groups are surprising given that they differ in both experience in The vOICe and in visual ability (sighted or impaired). For example, past findings showed that congenitally blind children did not exhibit an ear bias for speech, in contrast to sighted people (Larsen & Hakonsen, 1983). Furthermore, past work has also found hemispheric differences between experts and novices in terms of musical experience for recognizing melodies (Bever & Chiarello, 1974), whereas in the present study experienced and novice groups did not differ when perceiving The vOICe stimuli. It is worth noting that the experienced vOICe users did not report being familiar with recognizing letters specifically, and in fact perhaps had little use for such visual symbols in their daily lives.

A dichotic listening test to assess hemispheric laterality would be interesting as a pre- and post-test in training users with The vOICe. The limited sample size here, restricted by the small number of naturally occurring vOICe users available, may have not provided enough statistical power to detect a difference between the novice and experienced vOICe user groups in hemispheric lateralization. In Experiment 2, for vOICeDLT, only one out of five of The vOICe experienced users had a right hemisphere bias, and the other four out of five had a left hemisphere bias. This is compared to the sighted participants in Experiment 2, where the hemispheric bias for The vOICe was more widely distributed: four out of 15 had no hemispheric bias, six out of 15 had a right hemisphere bias, and five out 15 had a left hemisphere bias. Finally, no novice participants had as strong a left hemisphere bias as two of The vOICe experienced users. Yet these possible biases were, on average, no different from zero and thus have a bilateral characteristic.

These findings suggest that, initially, letters heard with The vOICe are not processed as either music-like or language-like stimuli (“non-melodic hums”; (Van Lancker & Fromkin, 1973)). In terms of the links between visual-to-auditory sensory substitution and language (Bach-y-Rita & Kercel, 2003; Deroy & Auvray, 2012) and visual-to-auditory sensory substitution and music (Abboud et al., 2014; Haigh et al., 2013), it is possible that the lack of hemispheric bias in the visually impaired group suggests that the processing of visual-to-auditory information is equally similar to both language and music processing; it may require features of both language processing, such as processing information with high temporal precision (Belin et al., 1998) and music processing, such as pitch processing (Peretz & Zatorre, 2005) in equal measure. Alternatively, it is possible that processing of visual-to-auditory information is similar to neither language nor music processing, but this is less likely as the features mentioned above are possibly necessary in visual-to-auditory information processing.

However, there are other possible explanations. The bilaterality, or possible lack of hemispheric bias, found in the results could partly arise because the vOICeDLT task may have been too difficult. Indeed, after completing the study, some of the visually impaired participants expressed that they had had difficulties with vOICeDLT due to print not being widely used by them. This is reflected in the fact that, despite having considerably more experience with The vOICe, and the fact that visually impaired people perform more accurately during DLTs (Hugdahl et al., 2004), the experienced group was outperformed by the novice group in terms of correct responses during vOICeDLT. Many participant responses may therefore have been guesses, in which case one would expect the number of correct right and left responses to roughly even out, which would explain the lack of hemispheric bias seen in the analysis. Thus this is possibly a good indication of how new images are processed rather than how language-related images are processed.

Another explanation could be that the lack of significant hemispheric bias was due to the study's small sample size, and that the left hemisphere bias demonstrated by the visually impaired participants might be representative of the greater visually impaired population, despite not being significant in our analysis. Note that prior results demonstrating bilateral processing have also been established on the basis of a non-significant hemispheric bias in a small sample (Güntürkün et al., 2015). Yet, if a left hemisphere bias were the case, then, the outcome of the study would be consistent with past research with respect to a tendency for a left hemisphere bias in speech processing (Alho et al., 1998; Doreen Kimura, 1967). If this were the case it might suggest that the processing of visual-to-auditory information is more similar to that of language rather than music.

Regarding the lack of differences found in hemispheric lateralization of visual-to-auditory processing between experienced and novice participants, it is possible that the hemispheric lateralization in the auditory cortex for visual-to-auditory information processing is not influenced by experience or training; this might stand in contrast to prior research with the hemispheric lateralization for recognition of melodies (Bever & Chiarello, 1974) where expertise impacts hemispheric lateralization. This also contrasts with prior work on visual impairment with perhaps some impact on hemispheric lateralization for speech processing (Larsen & Hakonsen, 1983). This is still compatible with previous research such as that by Pollok et al. (2005) and Ward and Meijer (2010) suggesting that there may be cerebral differences in visual-to-auditory information processing between experienced and novice users; however, it is possible that differences may not be present, or at least noticeable, in the auditory cortex, but instead limited to the visual cortex. Explanations based on the limitations stated above could also apply. For example, although found to be non-significant, the average score on the vOICeDLT was greater in the experienced group than in the novice group, suggesting a greater left hemisphere bias.

The results from the DLT for the novice group were consistent with previous research that suggests there is a left hemisphere bias for speech processing, especially in right-handed people (Alho et al., 1998; Doreen Kimura, 1967; Knecht et al., 2000). This suggests that the DLT adapted from the iDichotic app (Bless et al., 2013) was an effective way to collect information regarding hemispheric lateralization. Further research should therefore look into replicating the present study but using alternative stimuli for vOICeDLT. Instead of letters, which participants in the present study struggled with, soundscapes of familiar shapes such as houses and cars may be more suitable for the visually impaired participants as these are the shapes they are more likely to encounter using The vOICe. This may give more accurate estimations for participants' hemispheric lateralization of visual-to-auditory information. Furthermore, future studies should compare three or four groups instead of just two, adding a visually impaired novice group and, if possible, a sighted experienced group. This will help to distinguish whether differences in hemispheric lateralization, if any are found, are down to expertise or sightedness.

In terms of the questions raised by Kristjánsson and colleagues (2016) concerning whether using The vOICe with just one ear may be more effective than with two, the present study suggests, if indeed the lack of hemispheric bias in the processing of visual-to-auditory information is representative of the wider population, that continuing with two ears may be advisable. However, future research should also be conducted specifically testing the effectiveness of using The vOICe and other SSDs with two ears versus one, regardless of whether there is or is not a hemispheric bias, as it is still possible that visually impaired persons would benefit more from SSDs if one ear were free to attend to ambient sounds. Certainly there might be information processing capacity limitations with the simultaneous use of an SSD and monitoring of the environment (Brown & Proulx, 2016), and this would need assessment in future studies of the ergonomics of SSD use.

In conclusion, our study tested the hemispheric lateralization for processing visual-to-auditory information in visually impaired, experienced users of The vOICe and whether this hemispheric lateralization was different for sighted novices. We found that that there is neither a hemispheric bias in the processing of visual-to-auditory information in visually impaired, experienced users of The vOICe, nor that there is a difference in hemispheric lateralization of the processing of visual-to-auditory information between visually impaired, experienced vOICe users and sighted novices. Although standard dichotic listening is lateralised to the left hemisphere, the auditory processing of images in SSDs is bilateral, possibly due to the increased influence of right hemisphere processing. Auditory SSDs might therefore be equally effective with presentation to either ear if a monaural, rather than binaural, presentation were necessary or preferred. Sensory substitution provides a novel approach to study issues of lateralised brain function given that it provides a novel auditory stimulus, unlike language, and has the potential for applied impact as assistive technology for the visually impaired.

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Figures

Figure 1. Experiment 1 data for standard Dichotic Listening Test (SDLT) and vOICe Dichotic Listening Test (VDLT) results. All participants in Experiment 1 were sighted, novice (non-experienced) users of the vOICe. The values along the Y-axis indicate the laterality index (LI), with values above 0 indicating a right ear advantage, and values below zero indicating a left ear advantage, with the bar indicating the mean LI and the circles the individual values for each participant.

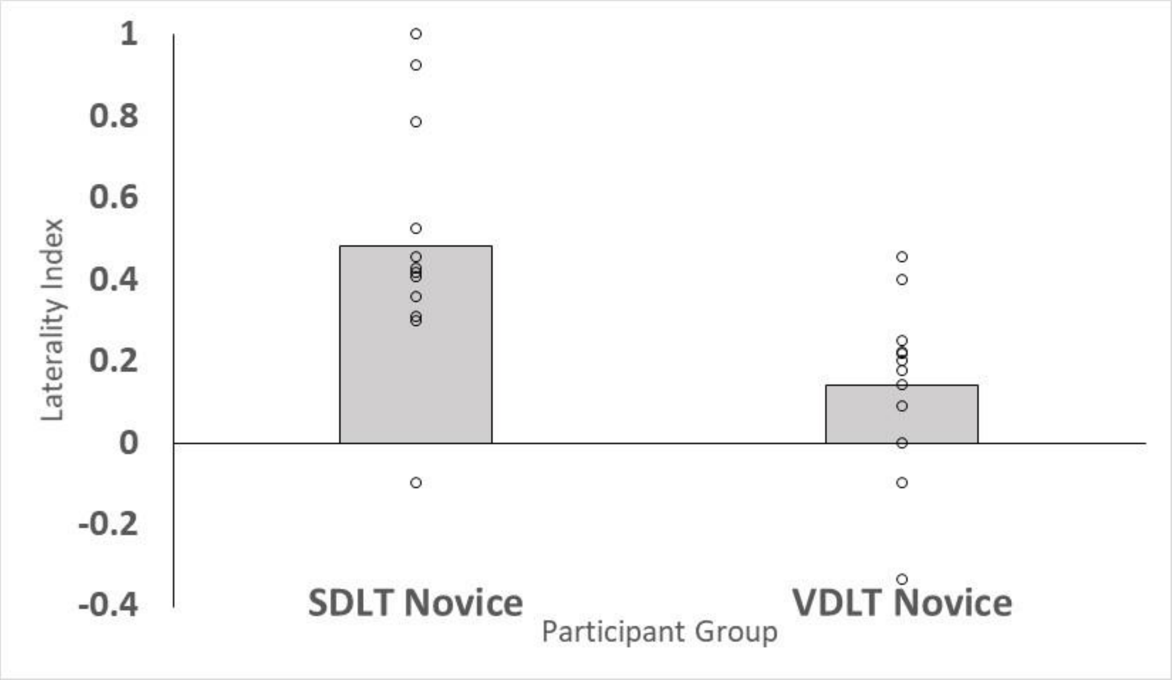

Figure 2. Experiment 2 data for the standard Dichotic Listening Test (DLT) results using iDichotic. Participants were either blind or sighted, and this is indicated on the X-axis. The values along the Y-axis indicate the laterality index (LI), with values above 0 indicating a right ear advantage, and values below zero indicating a left ear advantage, with the bar indicating the mean LI and the circles the individual values for each participant.

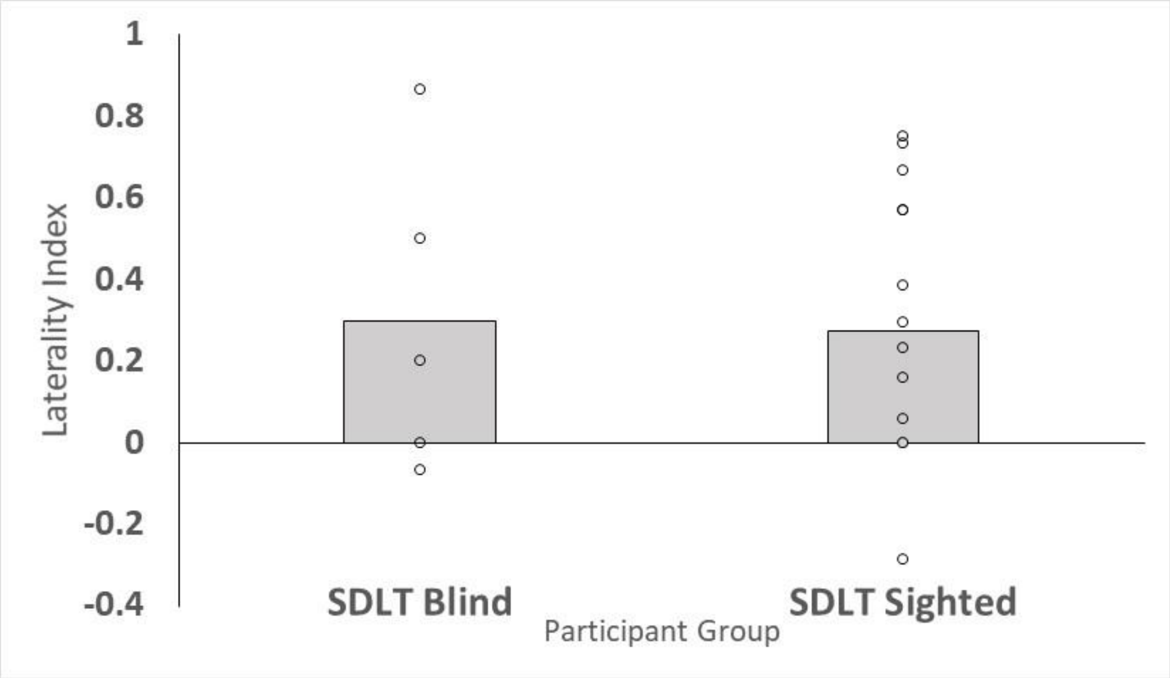

Figure 3. Experiment 2 data for the vOICe Dichotic Listening Test (VDLT) results using iDichotic. Participants were either the blind experienced users or the sighted novices, and this is indicated on the X-axis. The values along the Y-axis indicate the laterality index (LI), with values above 0 indicating a right ear advantage, and values below zero indicating a left ear advantage, with the bar indicating the mean LI and the circles the individual values for each participant.

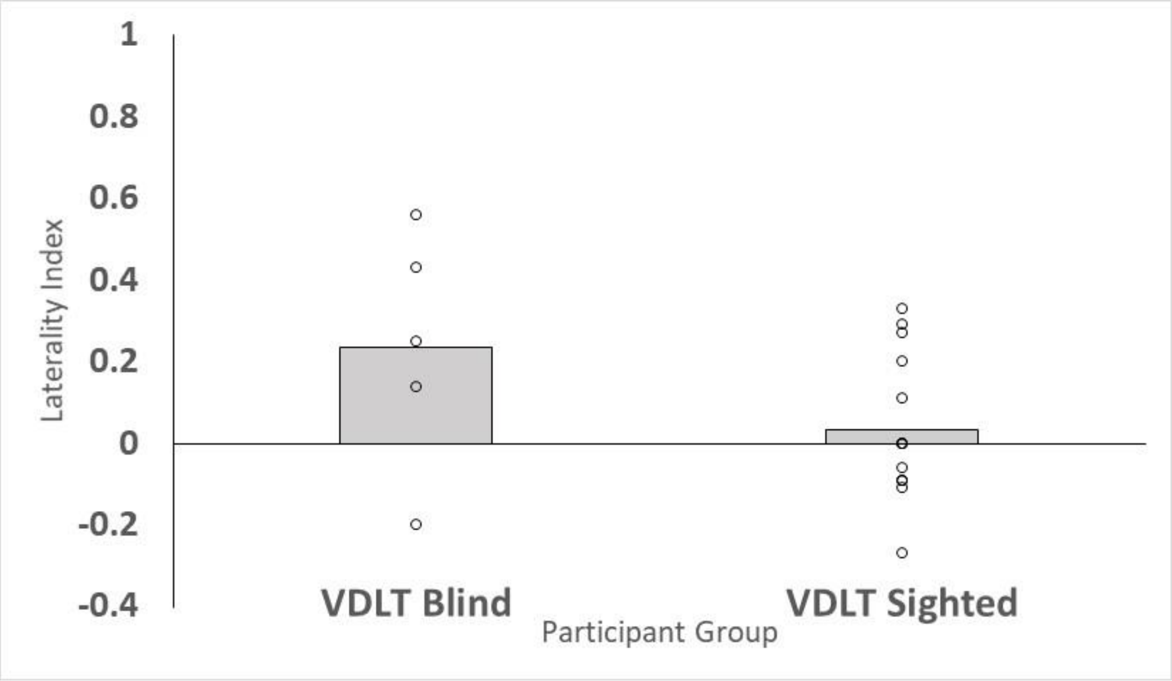

Table 1.

Hemispheric lateralization for different dichotic listening paradigms.

Experimental paradigm	Example Reference	Hemispheric bias	Ear advantage
Words / nonsense syllables	Kimura (1967)	Left	Right Ear
Tones used in linguistic decisions	Zurif (1974)	Left	Right Ear
Melodies	Kimura (1964)	Right	Left Ear
Complex pitch perception	Sidtis (1982)	Right	Left Ear
Nonmelodic hums	Van Lancker & Fromkin (1973)	Bilateral	No Ear Advantage
Turkish whistling	Gunturkun et al. (2015)	Bilateral	No Ear Advantage

Table 2.

Characteristics of the visually impaired users of The vOICe who participated in Experiment 2. "--" signifies no response

Age	Age of impairment	Visual impairment	Duration of vOICe use	Frequency of vOICe use	Experience in vOICe use (self-rated from 1-10)
31	0	Leber congenital amaurosis	5 years	Rarely	7
73	--	--	4 years	Twice per week	3
44	33	Traumatic Brain Injury	8 years	Depends	6
48	21	Retinitis Pigmentosa	several years	Not often	2
22	0	Retinopathy of prematurity	16 years	Twice per day	6
60	21	Work accident	18 years	Daily	8