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Functional recruitment of visual cortex for sound encoded object identification in the blind

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Abstract

Individuals using a visual-to-auditory sensory substitution device (SSD) called ‘The vOICE’ can identify objects in their environment through images encoded by sound. We have shown that identifying objects with this SSD is associated with activation of occipital visual areas. Here, we show that repetitive transcranial magnetic stimulation (rTMS) delivered to a specific area of occipital cortex (identified by functional MRI) profoundly impairs a blind user’s ability to identify objects. rTMS delivered to the same site had no effect on a visual imagery task. The task and site-specific disruptive effect of rTMS in this individual suggests that the cross-modal recruitment of occipital visual areas is functional in nature and critical to the patient’s ability to process and decode the image sounds using this SSD.

Keywords

blindness; occipital cortex; plasticity; repetitive transcranial magnetic stimulation; sensory substitution

Introduction

Humans rely heavily on vision to characterize shapes and identify objects in their environment. Auditory cues can also help to identify objects (for example, a dog by its barking), but sound typically provides little information that characterizes an object’s shape. Visual-to-auditory sensory substitution devices (SSD) have been developed as a means of providing visual information to the blind through spectrographic sound synthesis based on an input image [1–6]. Using a video camera linked to a standard personal computer and stereo headphones, a device called ‘The vOICE’ captures visual images and converts these into soundscapes according to a predetermined algorithm that encodes complex shape, shading, and texture information. In brief, vertical location is represented by frequency, horizontal location is represented by stereo panning, and brightness is encoded by loudness (for complete details, see <http://www.seeingwithsound.com> and Ref. [7]). With sufficient

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training, an individual can learn to use the device to identify actual objects and locate them in space through sound [1,2].

In a previous functional MRI (fMRI) experiment, we have shown that identifying common objects (through sound as defined by The vOICE algorithm) leads to activation of a network of cortical areas including early, peristriate occipital visual areas [1]. To examine the functional nature of this cross-modal reorganization, we explored the causal link between the ability to use The vOICE and the role of occipital visual areas in patient P.F., a late blind and highly proficient user of this SSD. Specifically, we used low-frequency (1 Hz) repetitive transcranial magnetic stimulation (rTMS) to transiently disrupt activity within this occipital cortical area. Impairment in performance after rTMS would support a causal link between activity in visual cortical areas and object identification performance using this device. Identifying objects using The vOICE, however, might also be the consequence of engaging visual imagery [8] that in turn could be disrupted by rTMS [9] and lead to a similar performance impairment. Therefore, we also investigated the impact of rTMS to the same occipital target on a spatial letter imagery task. An impairment in performance on the visual imagery task after rTMS application would support a causal link between activity in this visual cortical area and visual imagery and suggesting that the use of The vOICE may be related to visual imagery.

Methods

Case report

Patient P.F., a 53-year-old, right-handed woman with normal hearing, had had normal vision up to the age of 21 years, when she became profoundly blind because of a chemical explosion accident. Since that time, her residual vision has been limited to faint light perception in her right eye (the left eye being enucleated). Over the past 10 years, she had become highly proficient in using The vOICE and uses it daily to identify objects, navigate within her environment, and perform her daily activities.

Stimuli and experimental procedure

Written informed consent was obtained from the patient before participating in the study. The study protocol was approved by the investigational review board of Beth Israel Deaconess Medical Center and carried out according to the tenets of the Declaration of Helsinki.

Twelve common objects were chosen for the experiment (Fig. 1a). To make the task more challenging, we used objects scaled down from their actual size (e.g. a toy horse and a sail boat) and some objects were similar in shape and category (e.g. a hammer and wrench). During an initial familiarization run, the patient was presented with the test objects and asked to name them using The vOICE and was also allowed to explore the objects haptically. Correct identification was verbally confirmed by one of the experimenters. After the familiarization run, objects were presented in a random sequence and patient P.F. was asked to identify the objects using only the soundscapes generated by The vOICE device. During testing, the patient was not allowed to explore the objects by touch at any time before identification. Verbal responses were collected. Given the limited physiological time-window for rTMS effects [10], the patient was instructed to respond within 200 s after the presentation of each object so that the maximum time for exploring all the objects in an experimental block would be no more than 40 min. After the object familiarization run, patient P.F. was able to respond and identify all the objects within this time constraint. Experiments were filmed and reviewed for accuracy.

For the visual imagery experiment, we used a modified version of a letter identification task previously validated by members of our group and others [11,12]. In brief, the task requires the patient to mentally imagine the 26 letters of the English alphabet in upper case and block letter form. Before the experiment, patient P.F. was asked to draw each letter to confirm that her mental representations were correct and corresponded to the target letter form. During the experimental task, four ‘probes’ were used to query the spatial properties of each letter. The probe ‘two’ would query whether the target letter had two terminators; ‘close’ for whether the letter contained an enclosed space; ‘diag’ for whether a diagonal line was present and ‘sym’ for whether the letter had vertical symmetry (for examples, see Fig. 1b). During the task, a letter was presented auditorily followed by a brief interval of 1 s followed by a probe. The patient was instructed to respond ‘yes’ or ‘no’ to the letter-probe combination as quickly as possible. In an experimental block, 28 letter-probe pairs were used and presented in random manner. Verbal responses and response times were collected.

Transcranial magnetic stimulation procedure

High-resolution anatomical and functional images were obtained from a previous study where the patient performed a similar object identification task using The vOICE [1]. The images were used to identify the site of left occipital peristriae cortical activation implicated in this task and the eventual target site of stimulation (Fig. 2a and b). Correct placement and constant stimulation of the target site was insured by using a frameless stereotaxic device (BrainSight, Rogue Research, Montreal, Canada; Fig. 2b). Phosphene thresholds (determined using a method of limits and defined as the lowest stimulus strength evoking the perception of a phosphene in three out of five consecutive trials [13]) were also assessed before and after use of The vOICE. Once the optimal site for eliciting phosphenes and the phosphene threshold was determined, the output of the stimulator was fixed and the ability to perceive phosphenes over a series of different cortical sites was assessed in random manner. Phosphene detection was scored as present for a given cortical site if they were perceived in at least two out of three randomized attempts. The behavioral effects of rTMS were collected over two experimental sessions and following two different experimental designs (Fig. 1c). In a first set of experiments (experiment 1, Fig. 1c), the effects of rTMS on object recognition using The vOICE and on visual imagery were investigated using an ‘off-line’ protocol (i.e. task performance was assessed before and after rTMS for a given task and at a given cortical site). Low-frequency (1 Hz) rTMS was delivered at 75% of maximum stimulator output for 15 min using a standard figure-of-eight coil attached to a Magstim TMS device (Magstim Inc., Whitland, UK). A previous study has shown that these stimulation parameters are effective in disrupting visual cortical activity and tolerable to the study participant [14]. For the control experiment, rTMS was delivered to the vertex of the skull using the same intensity, frequency, and duration. A second set of experiments was carried out on another day (experiment 2, Fig. 1c). Baseline task performance was assessed and then rTMS was delivered to the occipital cortical target site using sham stimulation. This was accomplished by placing the stimulating coil tangentially and juxtaposed to a second inactive coil placed normally over the target site. This coil orientation minimizes the current induced in the patient’s brain, whereas it preserves the nonspecific effects of stimulation such as the audible click and surface scalp contractions [15]. After sham stimulation, task performance was reassessed. After a 30-min washout period, the same occipital site was stimulated again, this time with real rTMS, and task performance along with recovery time profile were evaluated (recovery was defined as the time taken to correctly identify four out of five consecutive objects, i.e. 80% correct performance). Importantly, during the entire set of experiments, the patient was naive as to the nature of the experiment, stimulation parameters used, and the rationale behind the chosen target sites of stimulation. Statistical analysis was carried out to compare percentage correct responses

and reaction times before and after rTMS (SPSS statistical software package; Chicago, Illinois, USA).

Results

Assessing patient P.F.'s phosphene threshold before and after approximately 3 h of object recognition using The vOICE resulted in a marked decrease in measured thresholds from 64 to 40% (maximum stimulator output) showing that occipital cortex excitability had increased after prolonged use of the SSD. Furthermore, patient's ability to perceive phosphenes at a variety of cortical sites (stimulator output set at the baseline phosphene threshold of 64%) was also tested. Visual inspection of the sites where patient P.F. reported perceiving a phosphene revealed that they were all limited to the left hemisphere and generally localized around the target cortical site identified previously by fMRI (Fig. 2b).

In both experiments, 1-Hz rTMS delivered over the occipital peristriate cortical target led to a dramatic impairment in patient P.F.'s ability to identify objects using The vOICE (Fig. 3a and b). In the experiment 1, baseline performance on the object identification was 75.0% and identification decreased to 25.0% correct after rTMS delivery over the occipital target. A significant association was found between baseline and post-rTMS performance [$\chi^2(1,24) = 6.00, P < 0.05$]. After a 24-h rest period, the control experiment was carried out using the same procedure but targeting the control site (vertex). Baseline performance on the object recognition was 58.3% correct, whereas after rTMS performance was 41.6% correct, yielding no significant association [$\chi^2(1,24) = 0.667, P > 0.05$]. Moreover, we compared performance from the two baselines (before rTMS over the occipital and over the control site) and no significant association was found [$\chi^2(1,24) = 0.750, P > 0.05$]. In the experiment 2, baseline performance on the object recognition task was 83.3% correct and following sham stimulation over the occipital cortical target, performance was 66.7% correct. Object recognition after real rTMS to the same site dropped to 16.7% correct. A significant association between baseline, post-sham rTMS, and post-real-rTMS performance was observed [$\chi^2(2,36) = 11.70, P < 0.05$]. Post-hoc comparisons revealed the largest difference to be between the standardized residuals of baseline and post-real-rTMS performance. A smaller difference between standardized residuals for baseline and sham rTMS indicated a lesser contribution to the significant outcome. It is worth noting that the magnitude of the effect on object recognition performance was comparable in both the experiments after real rTMS to the occipital target site (a reduction of 50.0 and 66.6% in experiments 1 and 2, respectively). After real rTMS in experiment 2, we monitored patient's recovery profile and found that the time taken to correctly identify four out of five consecutive objects occurred at approximately 50 min after the end of rTMS delivery.

Inspection of her verbal responses revealed dramatic errors in identification (e.g. 'giraffe' for a wrench and 'spider' for a hammer). This suggests that her errors in identification seemed to be related to an impairment of her overall interpretation of the soundscapes and not limited to categorical or scaling confounds (supplementary data Table 1 for complete list of verbal responses). Interestingly, patient P.F. reported a darkening sensation during and after rTMS delivery to the occipital cortical target. Subjectively, she found the object identification task extremely difficult and felt very uncertain of her responses. She described the objects as 'less distinct', 'not as crisp', and she reported that she could not separate details and edges. Furthermore, she reported that she had to 'carefully listen to the details in the soundscapes' rather than just 'seeing' with the soundscapes as she normally does. The control stimulations did not result in any similar sensations nor did she report having any difficulty in interpreting the soundscapes.

Finally, comparing performance on the visual imagery task before and after rTMS showed no significant difference for both the occipital and control target sites. Specifically, performance and response times prior and after stimulation of the occipital target were not statistically different [performance: $\chi^2(1,56) = 1.018$, $P > 0.05$; response times: $t(1,27) = 0.432$, $P > 0.05$]. Similarly, no statistically significant difference in performance or reaction times was observed following stimulation of the control site [performance: $\chi^2(1,56) = 1.018$, $P > 0.05$; response times: $t(1,27) = 0.402$, $P > 0.05$]. After rTMS at either cortical site, she did not report any subjective sensations similar to what was experienced in the object identification tasks with The vOICE nor did she report any difficulty in visualizing the letters.

Discussion

Previous studies have shown that early and late blind as well as sighted patients can learn to use visual-to-auditory-based SSDs to identify objects in their environment [1–6]. Studying patient P.F. provided an opportunity to investigate the causal relationship between cross-modal plasticity and the functional recruitment of occipital visual areas associated with using an SSD. Her unique expertise also allowed us to study the performance associated with extensive and prolonged use of The vOICE device. Our findings further support the notion that occipital cortex is cross-modally recruited to process input from other sensory modalities following visual deprivation [16–18].

Targeting an occipital cortex site with rTMS led to a dramatic impairment in patient P.F.'s ability to identify objects using The vOICE. Furthermore, her performance recovered to baseline levels within 50 min of stimulation which is in accordance with recovery times reported in studies describing task disruption following occipital cortex rTMS (e.g. Ref. [19]). Given that this same site was activated during object identification using this SSD (as revealed by fMRI), we might deduce that this activation is functional in nature and that this cortical area has been cross-modally recruited for this purpose. It is possible that the effect of rTMS is not limited to the site of stimulation but rather reflects the disruption of an extended network of long-range neural connections implicating cortico-cortical or even cortical-subcortical connections. We thus conclude that either the occipital cortex or its connected structures are causally related to object identification performance using The vOICE but cannot with certainty establish that the behavioral impact comes from the targeted brain region alone.

It is interesting that prolonged use of The vOICE device (on the order of hours) was also associated with a marked increase in overall occipital cortex excitability (as evidenced by a decrease in phosphene threshold). Furthermore, the perception of visual phosphenes was restricted to cortical areas within the general vicinity of the target cortical site activated during object identification (essentially localized to the left hemisphere). Curiously, the patient reported that during and after rTMS delivery to the occipital target site, she experienced a 'darkening' in her overall mental perception, although we cannot quantify the nature of this subjective description. Still, the convergence of these neural correlates further strengthens the argument that object recognition using this SSD may be associated with a localized area cross-modally recruited for this purpose.

In stark contrast, this dramatic disruption in performance was not observed when the patient carried out a visual imagery task. Therefore, we propose that the disruptive effect seen in patient P.F. after rTMS may result from the interruption of the specific behavioral ability of extracting spatial and identity information encoded by the SSD algorithm as opposed to her ability to engage visual imagery or discern pitch or sound intensity. After the rTMS, visual

imagery (albeit for a different task) was not affected, and patient P.F. could still clearly understand spoken instructions without any difficulty.

A similar cross-modal disruptive effect on spatial discrimination in the tactile domain was reported by Zangaladze and colleagues [20] and later by our group [19]. In these studies, focal TMS delivered to an occipital target in sighted patients led to a disruptive effect on a tactile grating orientation discrimination [20] and a distance spacing task [19]. It is interesting to speculate on whether the occipital networks targeted (and thus, implicated) are similar in all these studies. Furthermore, these findings support the notion that the occipital cortex may be part of a network related to the cross-modal analysis of an object's spatial information, regardless of the sensory modality that provides the information [1,17].

The results of this case study are in agreement with a recent independent study that also investigated the relationship between cross-modal plasticity and the use of an SSD. Collignon and colleagues [4] have shown that disruption of occipital cortex by rTMS (targeting right dorsal extrastriate region) impairs the ability to use an SSD in early blind users but not sighted controls. Specifically, rTMS interfered with spatial localization performance but did not interfere with pitch and intensity discrimination tasks (rTMS in sighted control participants did not lead to disruption in any of the auditory tasks studied). The authors suggested that the recruitment of occipital cortex was related to spatial information processing as opposed to strictly auditory information processing such as pitch discrimination [4]. Given that the aforementioned study focused on an early blind population, this study contributes to their findings regarding the causal effect of rTMS and the potential of cross-modal reorganization in late blind patients who use an SSD for complex shape and object recognition. It is, however, important to note that The vOICe device used in this study is somewhat different in terms of the encoding algorithms and hence the generated soundscapes. Furthermore, patients in the Collignon *et al.* [4] study were trained for a short training period before testing (total of 4 h) compared with the years of experience held by our patient using The vOICe SSD. These differences may also account for the dramatic effect observed in this study patient.

Given that patient P.F. is late blind, it is not possible to rule out definitively the possible role of visual imagery. In turn, the observed effect of rTMS may be the result of disrupting her ability to imagine the object [9] (for discussion, see also Refs [21,22]). In this study, no impairment in performance on a visual imagery task was observed (on performance nor reaction time) after rTMS delivery to the occipital cortical target. The lack of a disruptive effect does help dissociate the functional nature of the target site from a potential involvement in visual imagery. However, the lack of an effect should be interpreted with caution. In particular, it is not clear at this time whether performance on this particular visual imagery task recruits the same cortical networks, or at the very least, accurately reflects the same cognitive functions implicated with object recognition using The vOICe. Perhaps, designing a visual imagery task in which patient P.F. is instructed to mentally imagine and identify particular attributes of objects that she identifies using The vOICe would help disentangle this issue. It is important to realize, however, that designing such a task is difficult given that the patient P.F. is profoundly blind. Thus, we were somewhat limited in using objects with which she is familiar and shapes based on her prior visual experience, for example, letters of the alphabet (as used in the experiment described here). These limitations notwithstanding, evidence from our prior study further supports the notion that visual imagery alone cannot fully explain the results observed in this study. Specifically, sighted patients (who presumably have visual imagery intact, and therefore are likely to apply visual imagery to interpret soundscapes) did not show activation of early visual areas [1], despite the task's likely involvement of both high-resolution detail and spatial judgment [8]. Furthermore, early blind individuals (who presumably have impaired visual mental imagery

because of a lack of prior visual experience) have been shown to have a similar interference of visual-to-auditory identification of objects when rTMS is applied to their occipital cortex [4]. In addition, disrupted visual imagery would at first seem inconsistent with our previous fMRI findings showing that occipital cortex is not activated when object identification was carried out by simple auditory association as opposed to using The vOICe algorithm that explicitly encodes for shape [1]. In those cases, however, there was no visual structural data in the sounds to support bottom-up detailed visual imagery through mental reconstruction. Finally, high level performance with an SSD such as The vOICe may also be dependent on the patient's effort to recognize objects and visualize detail as with visual imagery [9] and dependent on its overall vividness [23]. A main goal for an SSD is to increase vividness and realism of cross-modally guided visual imagery for blind users, and all the aforementioned findings thus far seem to be consistent with this possibility.

Conclusion

rTMS delivered to a functionally guided occipital cortical target leads to an impairment in the ability to identify objects using an SSD in a late blind expert user. The site-specific disruptive effect in this individual suggests that the cross-modal recruitment of occipital visual areas is functional in nature and contributes to her ability to identify objects using the SSD.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Fig. 1. Experimental procedures and design. (a) Photo of the 12 objects used in the experiment. (b) Verbal probes and example responses used in the visual imagery experiment. (c) In experiment 1, performance was assessed before and after off-line repetitive transcranial magnetic stimulation (rTMS) was delivered to the occipital target and the control site (vertex). In experiment 2, baseline performance was compared with sham rTMS and then real rTMS at the same occipital target site.

Fig. 2.

(a) Transverse slice showing the site of functional activations in patient P.F. following object identification using The vOICE sensory substitution device (functional MRI; obtained in a previous experiment, [1]). The cross-hair intersection identifies the cortical site targeted with repetitive transcranial magnetic stimulation (rTMS). (b) Posterior view of the occipital pole of patient P.F.'s brain. The gray ring indicates the TMS coil position during stimulation and corresponding cortical projected location as seen in the functional activations in (a). The dark ring corresponds to the site of phosphene threshold (PT) determination. Sites filled in white and dark gray correspond to cortical targets where phosphenes were perceived and not perceived, respectively.

Fig. 3.

(a) Bar graph reporting the percent of correct responses as a function of site of stimulation (occipital cortex vs. vertex). Baseline (black bars) and post-(repetitive transcranial magnetic stimulation) rTMS performance (white bars) are reported. (b) Bar graph reporting the percent of correct responses at the occipital cortical site at baseline (black bar), following sham rTMS (gray bar) and rTMS (white bar). NS, not significant; * $P < 0.05$.