CHAPTER 6:

GENERAL DISCUSSION

Introduction

The broad themes of this thesis have ranged from crossmodal plasticity to automaticity (behavioral and neural), and rehabilitation of the blind population. Crossmodal plasticity is critical to the learning of any sensory substitution encoding, as sensory substitution inherently bridges across two modalities: the sense that receives the information, and that which interprets it. The automaticity of sensory substitution was studied both behaviorally (Chapter 3) and with neural imaging (Chapter 4). Automaticity of SS is critical to improving blind rehabilitation with sensory substitution, and the studies in this thesis will aid in the development of better training techniques and device encodings. Finally, blind rehabilitation has recurred as a theme throughout all of the thesis chapters, and is an important end application of this research.

Discussion

Crossmodal Plasticity

Crossmodal plasticity is the foundation of all sensory substitution learning. Through crossmodal interactions and then plastic changes of those interactions, sensory substitution stimuli are interpreted visually, and action is generated. The type of plasticity, whether strengthening or weakening of existing neural connections or the generation of new neural connections, likely depends on the task, duration of training, and visual deprivation of the participant (*i.e.,* blind or sighted).

The experiments in this thesis all rely on plastic changes across the senses to generate improved performance at sensory substitution tasks. The results of these plastic changes are measured behaviorally in Chapters 2 and 3, and with neural imaging (fMRI) in Chapters 4 and 5. In Chapter 2, the constancy processing of SS stimuli (after training) is likely mediated by visual neural regions that are activated by crossmodal plastic changes. Chapter 3 studied the underlying crossmodal mappings that are used in the interpretation of SS by naïve and trained users. Some intrinsic correspondence/mapping seemed to exist, mediating A-V matching performance in the trained as well as in the naïve participants. These crossmodal neural connections generating the crossmodal mappings are potentially strengthened via SS training to generate relevant improvements in performance. In Chapter 4 and 5, crossmodal plasticity is measured explicitly with fMRI scans before and after vOICe training. Chapter 4 determines whether the crossmodal plasticity can be activated automatically (*i.e.,* without attention) after training on an SS device. This was confirmed via a mental counting task that distracted attention while a vOICe encoding of white noise was played. In Chapter 5, the mapping from visual space through SS to visual activation is measured to determine whether the crossmodal plasticity is topographically mapped. Both Chapter 4 and 5 serve to better understand crossmodal plasticity with sensory substitution by testing its automaticity and spatial mapping.

Intrinsic Crossmodal Mappings

Intrinsic mappings across the senses (such as vision and audition) were shown to be important to sensory substitution interpretation in Chapter 3. Chapter 3 studied whether any vOICe sounds could be intuitive without any knowledge of vOICe by using the crossmodal mappings (such as matching a high pitch with a high spatial location) that participants already had. Surprisingly, the naïve could interpret vOICe sounds, and could do so automatically (independent of attentional load). Given this result in Chapter 3, it is likely that crossmodal mappings play a key role in the sensory substitution learning in each of the other chapters, and may even underlie a part of the visual activation in response to vOICe sounds.

Automaticity

Automaticity was the key concept in Chapters 3 and 4 to study the assumed cognitive (top-down) nature of sensory substitution interpretation. In general, SS is limited in its commercial prospects due to the long training time and the heavy cognitive burden of interpretation. Therefore, we have studied in this thesis ways to make SS more automatic. In Chapter 3, we investigated crossmodal mappings (such as matching a high pitch to high spatial position) to determine whether images and encodings with crossmodal mappings can be easy or automatic to interpret. We found that these intuitive and existing mappings made vOICe interpretation attention-load insensitive (*i.e.,* independent of attention) even in entirely naïve users. In Chapter 4, we investigated if the crossmodal plasticity generated by using SS can also be automatic. This fMRI experiment used a distraction task to test for attention-load sensitivity. The results showed that visual activation generated by crossmodal plasticity was not dependent on attention.

The study of automaticity and sensory substitution is quite novel. Because SS is assumed to be top-down and cognitively intensive (or rather, no researchers had paid attention to this dimension of top-down attentive *vs.* automatic), no studies have investigated whether there is an element of SS that might be intuitive or processed automatically. The study of intrinsic crossmodal mappings and their role in making SS interpretation automatic (in Chapter 3) is the first step in highlighting the automatic elements of SS and expanding their role in SS. The study of the automaticity of crossmodal plasticity following training with SS (Chapter 4) is a novel indication that plasticity engendered by SS usage can be automatic (*i.e.,* not require attention). These investigations may allow for improvements in training to tap into this automatic crossmodal plasticity and make SS easier to use.

This thesis provided two critical results on the automaticity of SS that should be emphasized. The first result, from Chapter 3, is that if existing crossmodal connections and mappings are optimally used in stimuli and encodings, then SS can be automatically interpreted. The second finding, in Chapter 4, indicated that crossmodal plastic changes engendered by training can be automatically activated independent of attentional demands. Combined, these results show that sensory substitution may have hope of becoming a more easily interpreted device, and consequently aid a wider blind population.

Blind Rehabilitation

Improving the capabilities of the blind is a major goal of sensory substitution as well as the research in this thesis. The blind are a large disabled population within the United States and around the world. An inexpensive and useful aid for the blind could help not only individuals in advanced countries, but also those throughout impoverished nations. Sensory substitution has the potential to be this device.

The research in this thesis aims to improve SS devices with psychophysical as well as neural imaging studies. In Chapter 2, the functional use of SS to externalize vOICe stimuli via shape and rotation constancy is an important step toward the processing of objects in space and in the correct proportion and orientation. Chapter 3 focuses on making SS easier to interpret by using intrinsic crossmodal mappings that users already have. More ease of use could make sensory substitution a better aid to the blind and therefore more widely utilized. Moreover, the results indicate that vision-like perception (in the sense of being effortless) can be accomplished via training potentially more easily than previously believed. In addition, Chapter 4 and 5 investigate the neural processing of SS, the results of which could be used not only to understand the neural mechanisms of multisensory plasticity, but also to optimize device training to generate more crossmodal plasticity from SS use. Greater crossmodal plasticity would improve device performance, and thereby enhance rehabilitation. Overall, the behavioral studies in Chapter 2 and 3 directly test methods to improve blind rehabilitation with SS devices with promising results, and the neural imaging in Chapters 4 and 5 use enhanced understanding of neural processing as tools to improve SS device usage. Not only that, a part of the results further confirmed the attentionless, automatic nature of the perceptual interpretation after SS training. Therefore, the results in this thesis are important steps toward making SS devices more intuitive and utilizing the potential of crossmodal plasticity to improve device interpretation.

Interaction of Thesis Themes

The roles of the thesis themes (detailed above) as tools, experiments, and end goals are spatially laid out in Figure 6.1. The major neural processing capabilities have been used as tools in this thesis, and include: Crossmodal plasticity and sensory motor learning, which were both used to train blind and sighted individuals to use the vOICe and to engender improvement during that training. The two major end goals from the experiments in this thesis are the rehabilitation of the blind and the advancement of neuroscientific understanding of multisensory mapping and plasticity, both of which were furthered in the execution of the thesis experiments. The vertical *y*-axis of Figure 6.1 shows that several chapters of this thesis are more basic-science-themed (the end aims are to advance the scientific understanding, rather than a material or physical goal). In contrast, other experiments are of a more applied-science nature, and strive to develop a device to aid the blind. Of course, the end goals have a moderate overlap across chapters, thereby generating the cross arrows.

An alternative method of visualizing the themes in this thesis is as a pyramid (Figure 6.2). The pyramids base blocks consist of the crossmodal plasticity and sensory motor learning, which then support two additional blocks: The automaticity of learning block, and then the blind rehabilitation block. With pyramid height corresponding to vOICe learning, each of the building blocks increases in vOICe learning, and is supported by the blocks beneath them. This visual analogy makes it clear why greater training techniques to enhance sensory motor learning and crossmodal plasticity are critical to the success of sensory substitution as an aid for the blind. If either of the foundation stones crumples, blind rehabilitation with sensory substitution will not succeed.

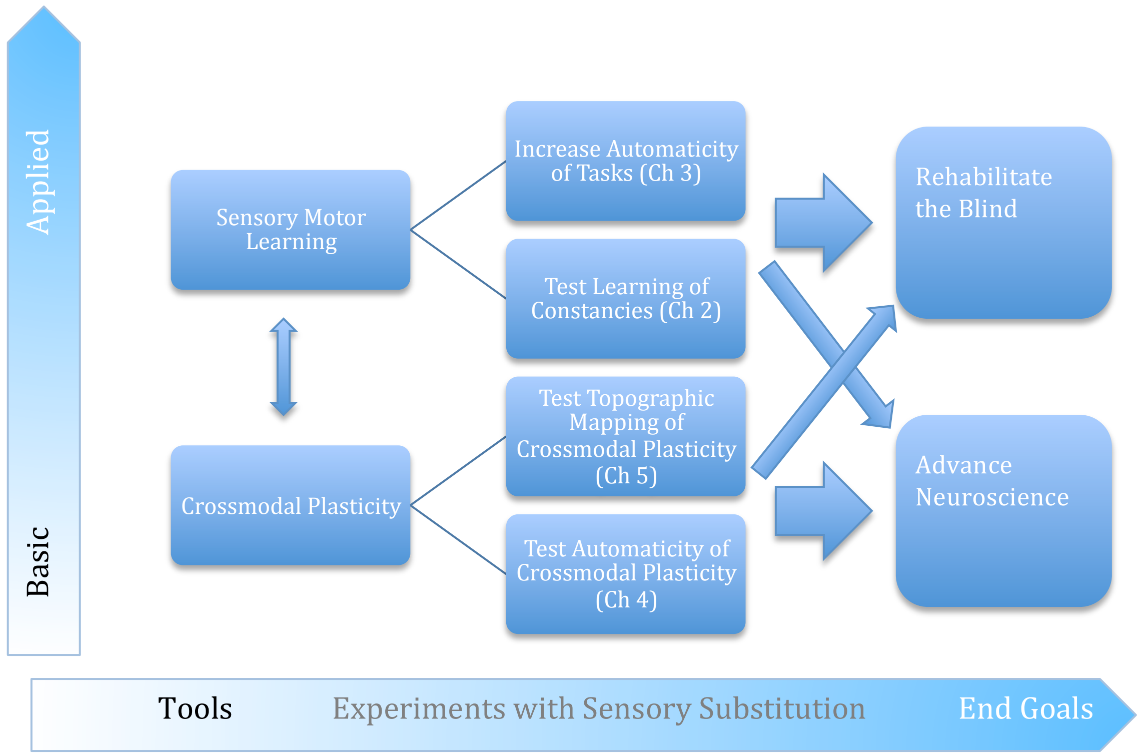


Figure 6.1. Concept web for thesis. This diagram spatially lays out the concepts developed in the thesis, and maps out several interesting inter-connections among concepts. In particular, it maps out the progress from tools to experiments to scientific goals for the thesis. It also shows the range from basic science to more applied science, and various cross-connections among the two.

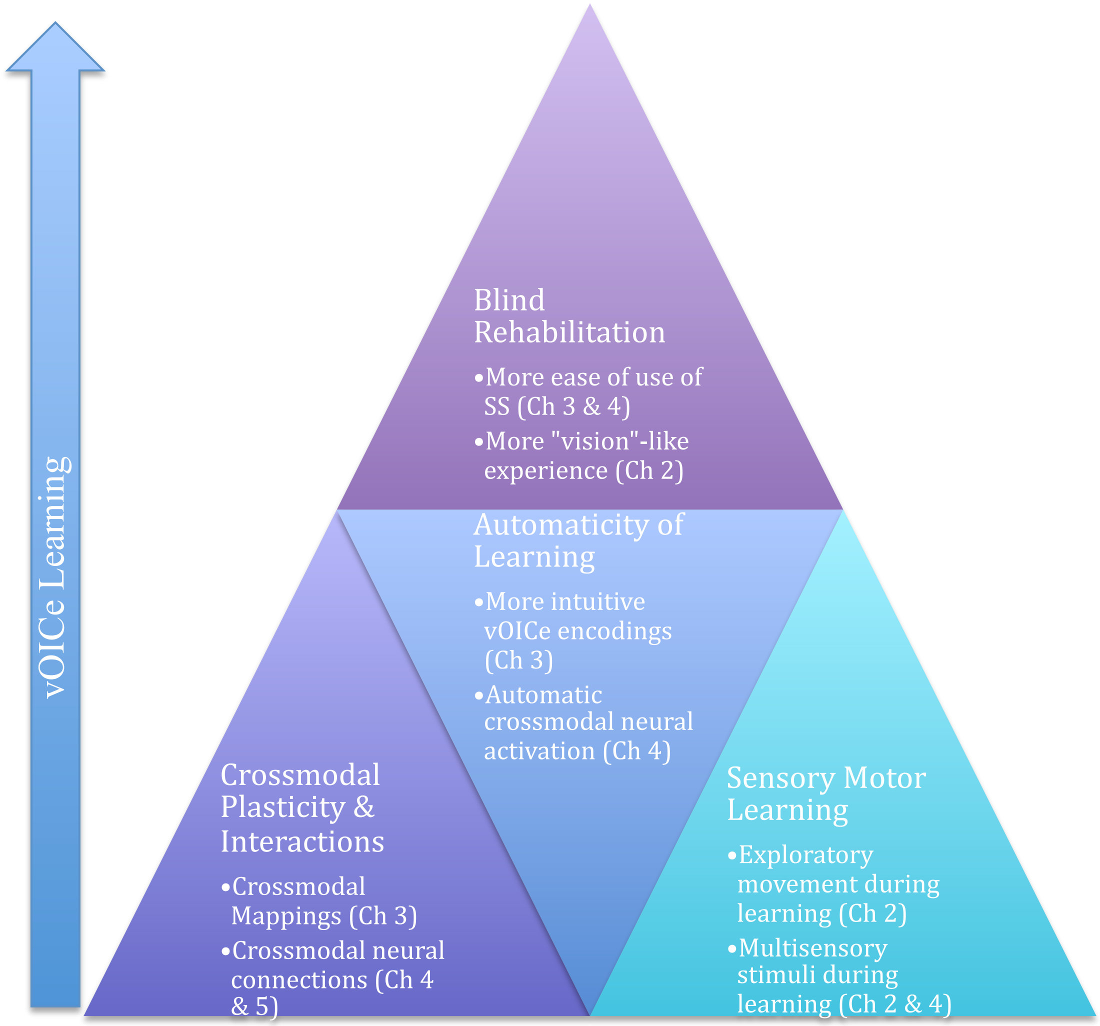


Figure 6.2. Layout of thesis themes. An alternative layout of thesis themes shows the crossmodal plasticity and sensory motor learning at the base of the pyramid, supporting the automaticity of perceptual processing and the rehabilitation of the blind. Each of the pyramid blocks has references to the chapters that relate strongly to those themes.

Research Next Steps

Research is a continuous process of discovery, and the studies in this thesis are just one step in a march toward understanding the brain. Therefore, there are several experiments and studies following on the work in this thesis that will continue to add to neuroscience. A few of these potential experiments are highlighted below.

Perceptual Constancy

Chapter 2 focused on the learning of constancies with the vOICe device; in particular, length constancy and shape constancy were learned by sighted and blind participants. Additional perceptual constancies would also be interesting to test with the vOICe device, such as size constancy (objects appear the same size independent of distance), which is valuable to monocular depth perception, or brightness constancy (objects appear the same brightness independent of lighting conditions), which is valuable to recognition and localization capabilities. Further, we tested constancies in a simplified lab setting; training and testing the use of constancies in daily-life tasks would be an important step toward full visual perception and capabilities. Such daily-life tasks may include recognizing and picking up an object on a table independent of object orientation (shape constancy) or lighting conditions (brightness constancy).

Neural Correlates of Intrinsic Crossmodal Mapping

In Chapter 3, it was shown that crossmodal correspondences generate the intuitiveness of different stimuli encoded by SS. This chapter used several behavioral psychophysical tests to determine the role of crossmodal mappings in sensory substitution interpretation, and the automaticity of interpreting crossmodal mapping-rich SS sounds. An interesting follow-up experiment would be to study the neural correlates of the interpretation of SS based on intrinsic crossmodal mapping. In particular, it would be interesting if intuitive sounds that are crossmodal mapping-rich also have more visual activation (via crossmodal interactions) than SS sounds that are crossmodal mapping-deficient. This correlation between crossmodal mapping intuitiveness and visual activation (due to crossmodal interactions/plasticity) would indicate the neural processing behind the use of crossmodal mappings to interpret SS effortlessly.

Correlation with Other Multisensory Effects/Tasks

Another experiment using the premise of Chapter 3 (*i.e.,* crossmodal interactions impacting SS interpretation) would study whether participants that have strong crossmodal interactions also find SS more intuitive and easy to learn. Tests of crossmodal interactions could include bouncing *vs*. streaming effect, the double flash illusion, or the McGurk Effect. There is also a range of SS tests that could be used for this experiment including localization, recognition, and depth perception. The more similar the crossmodal interaction and SS task, the more likely that they will use similar multimodal pathways and therefore be correlated. Therefore, the bouncing *vs.* streaming effect and movement evaluations of speed and direction in SS would be more likely to be correlated than bouncing *vs.* streaming and object recognition. This line of research, if further applied to the blind population (V-T mapping), may eventually provide us with a simple diagnostic test of suitability of SS to a particular individual.

Testing Effects of SS Training by Multisensory Illusions

In the same direction, SS training and the resulting crossmodal plasticity may impact the strength of existing crossmodal interactions. In this experiment, the strength of a crossmodal illusion could be tested before and after training on sensory substitution.

As with the comparison above, the more similar the SS training and the crossmodal interaction, the more likely that SS training will impact the strength of the crossmodal interaction. It is also more likely that crossmodal interaction strengthening will be detected if it is tested as soon after training as possible.

Suppression of Visual Cortical Processing by SS Training

In Chapter 4, fMRI imaging was used to test whether crossmodal plasticity from vOICe training was automatic (or engaged without attention). As a part of this chapter, it was found that visual activation due to a vision white noise pause detection task was suppressed following training relative to before training in sighted individuals. It would be interesting to determine whether this suppression effect only occurs with white noise images, or if it also occurs with other images and/or visual tasks. Further, does the visual suppression correlate with the amount of crossmodal plasticity in each individual? Deeper investigation of this suppression phenomenon may lead to interesting conclusions on the competition between visual and crossmodal processing in the brain.

Conclusion

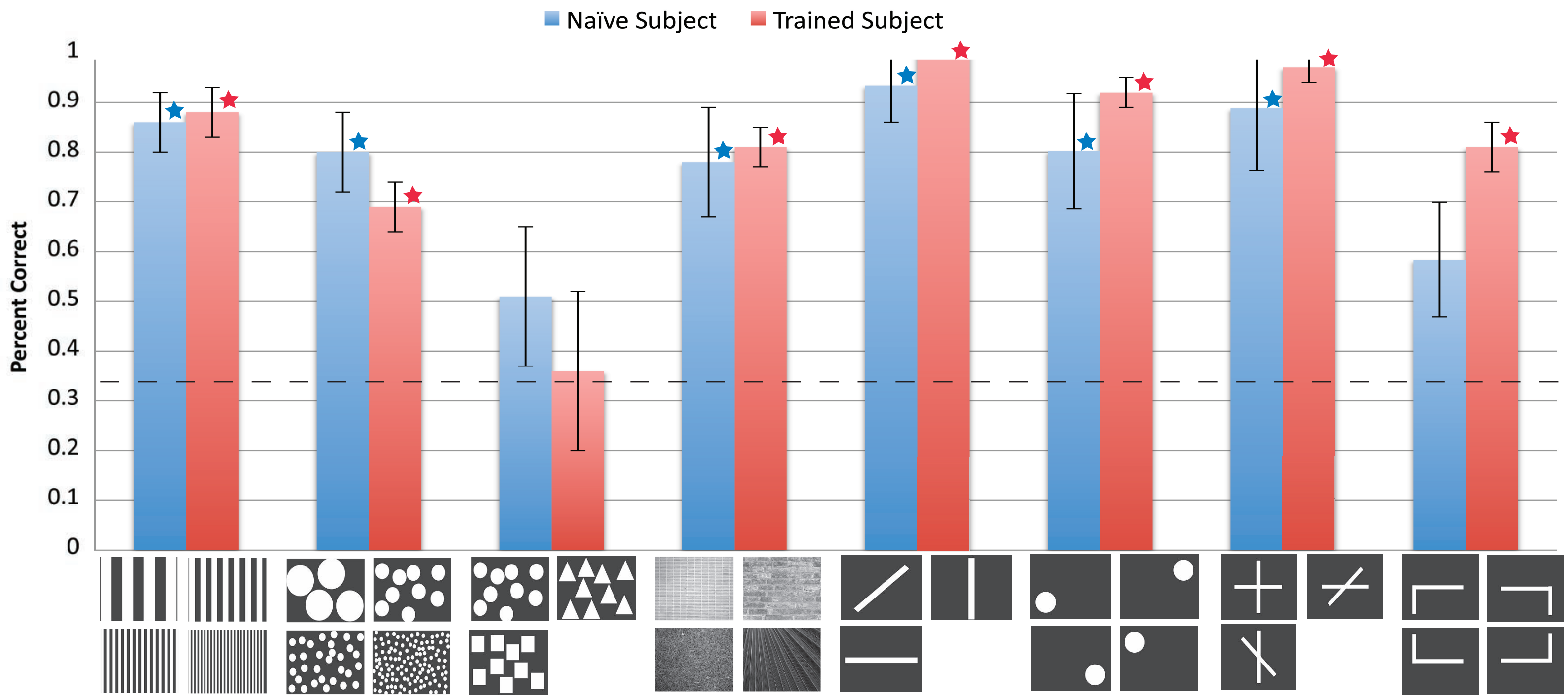
This thesis has used psychophysics and neural imaging to study crossmodal plasticity and improve blind rehabilitation with sensory substitution. The results contribute to the understanding of neural changes, and add new crossmodal methods to improving sensory substitution for blind rehabilitation. New experiments based on the results in this thesis are plentiful, including new studies on crossmodal mappings and SS crossmodal plasticity. New research will hopefully build upon this thesis's results to construct a better understanding of the brain, and through that understanding aid populations recover from neural deficits.

APPENDIX A

SUPPLEMENTARY DATA FOR CHAPTER 3

Figure A-C: This figure contains the task-performance matching images to vOICe sounds of naïve and trained participants for all image sets tested in Chapter 3. It also contains the pvalue threshold markers for the comparison to chance of naïve and trained data, as well as the naïve to trained comparison. The blue and red stars indicate that a given image set is significantly different from chance ($p < 0.05$) for the naïve and trained individuals, respectively. The purple stars indicate that the naïve and trained performance were significantly different from each other ($p < 0.05$).

Figure A



Naïve Subject
Trained Subject
Percent Correct
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Figure B

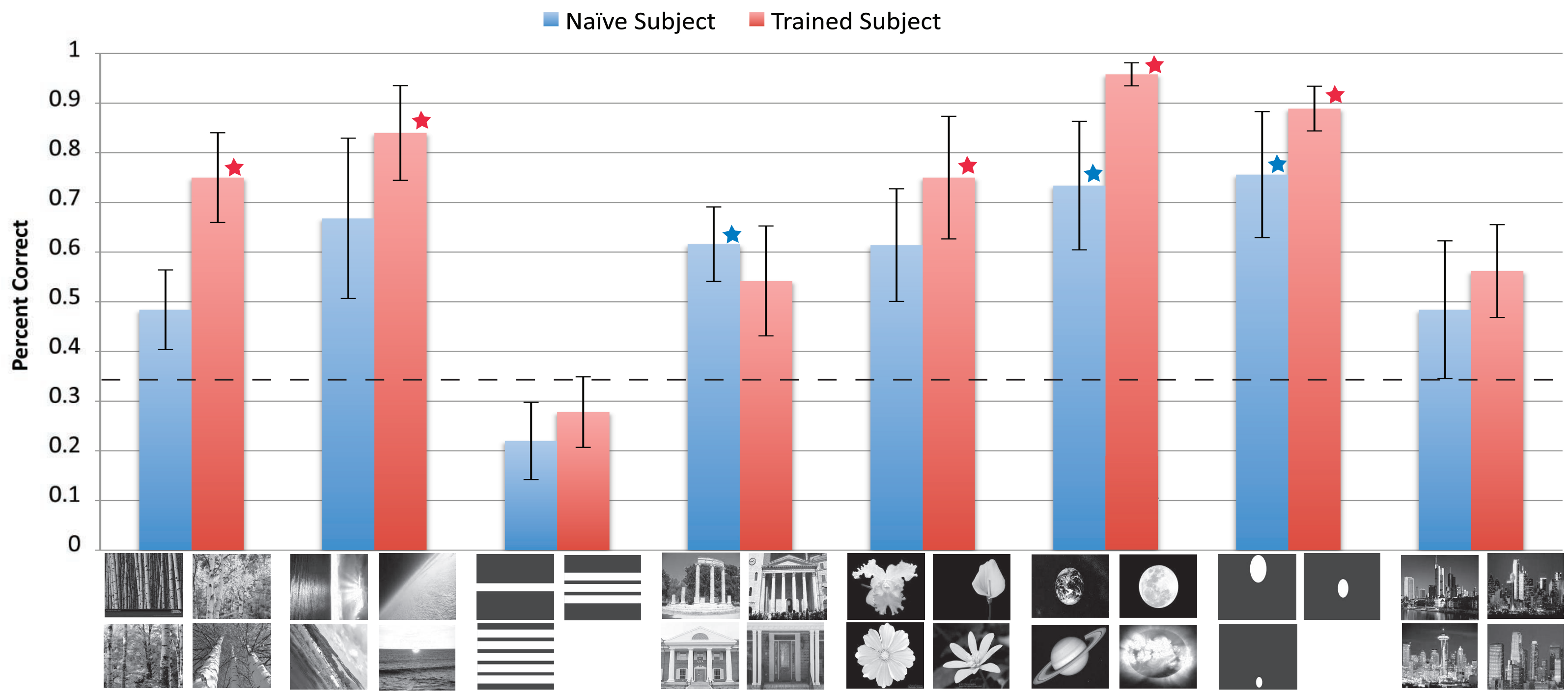
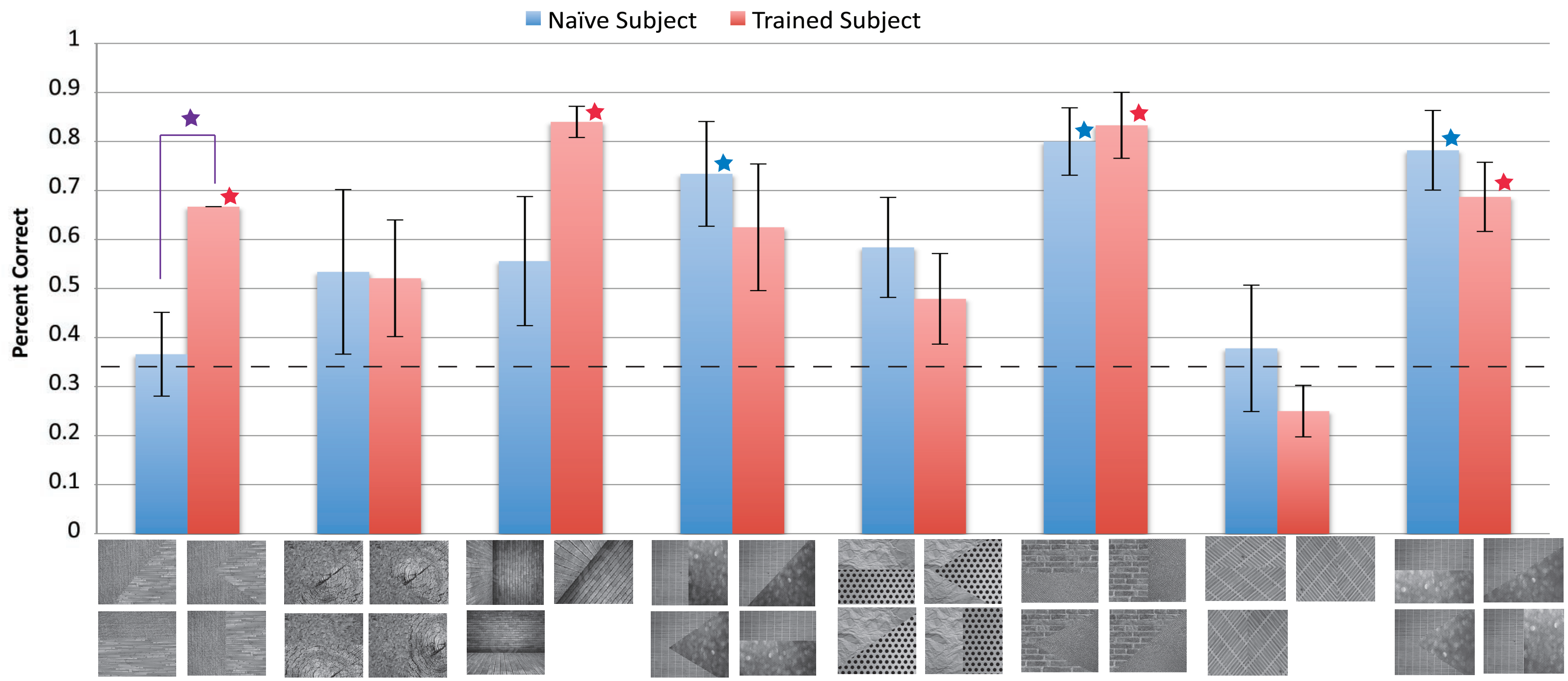

Naïve Subject
Trained Subject
Percent Correct
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Figure C


Naïve Subject
Trained Subject
Percent Correct
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

APPENDIX B

vOICE TRAINING PROCEDURES

This appendix includes the detailed training instructions for the fMRI vOICe experiment (Chapter 4 and 5) in part 1, and the vOICe behavioral experiments (Chapter 2 and 3) in part 2. The instructions were drafted before and during training as a guide to the experimenter on the training procedure. Additional detail was added following the experiments to clarify the training procedures.

Appendix B Part 1

vOICe fMRI Localization Experiment Training Instructions

Session 1 (1 hour)

- Training Assessment (always perform assessment first)
  - 10 trials of reaching for a white circle in one of five locations on a black felt covered board while sitting at a black-felt-covered table (positions randomized in MATLAB)
  - Record accuracy of reaching before physically correcting the participant's reach to the center of the circle.
- Training Tasks:
  - Locating, centering in the field of view and reaching for large circle on the black felt board (give feedback on the accuracy of centering before the participant reaches).
  - Differentiating between configurations of white blocks and shapes on the black felt board (L from a backwards L, from a 7 and a backwards 7, and a circle from a square, from a rectangle).

Session 2 (1 hour)

- Training Assessment (always perform assessment first)
  - 10 trials of reaching for a white circle in one of five locations on a black-felt-covered board while sitting at a black-felt-covered table (positions randomized in MATLAB)

   - Record accuracy of reaching before physically correcting the participant's reach to the center of the circle.
- Tasks:
   - Locating, centering in the field of view and reaching for large circle on the black felt board (give feedback on the accuracy of centering before the participant reaches).
   - Localize, walk to, and touch a large circle (5.5 inches in diameter) on a black felt wall. The participant must center the object, walk several steps, and then re-center the object in iterations until the participant is within reaching distance. The experimenter walks the participant through the first trial, and then in future trials, allows the participant to independently perform the task, only indicating when the participant is within reaching distance of the black felt wall. The circle can be placed on the center, left or right, and high, mid-level or low on the wall.

Session 3 (1 hour)

- Training Assessment (always perform assessment first)
   - 10 trials of reaching for a white circle in one of five locations on a black-felt-covered board while sitting at a black-felt-covered table (positions randomized in MATLAB)
   - Record accuracy of reaching before physically correcting the participant's reach to the center of the circle.
- Tasks:

- Localize, walk to, and touch a large circle (5.5 inches in diameter) on a black felt wall. The participant must center the object, walk several steps, and then re-center the object in iterations until the participant is within reaching distance. The circle can be placed on the center, left or right, and high, mid-level or low on the wall.
- Avoid a white chair obstacle on the way to localizing and reaching for a large circle on the black felt wall. The participant must locate the chair, avoid the chair without touching it, and then localize the white circle. The chair can be placed in front of the participant, or to the left or to the right of the participant.

Session 4 (1.5 hours)

- Training Assessment (always perform assessment first)
    - 10 trials of reaching for a white circle in one of five locations on a black-felt-covered board while sitting at a black-felt-covered table (positions randomized in MATLAB)
    - Record accuracy of reaching before physically correcting the participant's reach to the center of the circle.
- Tasks:
    - Avoid a white chair obstacle on the way to localizing and reaching for a large circle on the black felt wall. The participant must locate the chair, avoid the chair without touching it, and then localize the white circle. The

chair can be placed in front of the participant, or to the left or to the right of the participant.

- Differentiate five office objects (scissors, stapler, tape dispenser, tissue box, and envelope) at the black felt covered table and board. Participants are shown the objects with the vOICe device and then are asked to identify the objects when presented in random order (order generated by experimenter, not computer).
- Train for the fMRI Experiment: Perform the localization of a white dot on the left or right with 1. visual stimuli alone on computer, 2. simultaneous vision and auditory stimuli (*i.e.,* vOICe) on computer and then 3. just auditory stimuli (*i.e.,* vOICe) alone (this training bridges between the just auditory and just visual ends of the experiment).

Session 5 (0.5 hours)

- Training Assessment
  - 10 trials of reaching for a white circle in one of five locations on a black-felt-covered board while sitting at a black-felt-covered table (positions randomized in MATLAB)
  - Record accuracy of reaching before physically correcting the participant's reach to the center of the circle.

Appendix B Part 2

vOICe Behavioral Experiments Training Instructions

Note: Several different experiments were attempted in the pre- and post- training behavior sessions (session 0 and session 10), including the texture experiments (Chapter 3). The experiments listed in session 0 and session 10 are just examples of those tested.

Session 0 (1 hour) (Performed on iMac computer)

- Bouncing *vs*. Streaming Experiment
    - File: BounceVStream.m
- Moving Dot Experiment: Left-to-Right *vs*. Right-to-Left Rate Estimation Task (use headphones on table next to iMac computer)
    - File: vOICeVisIllExptMovDot2AFCQuarter.m

Session 1 (1 hour)

- Assessments Tasks:
    - Shape Constancy Test: 20 trials of participants assessing bar length (lengths 1-5) independent of angle. Perform task on vOICe, and then with normal vision. Note: Allow participants to see the line lengths vertical and horizontal with vOICe for each length before beginning the test **(allow head tilt).**
    - Rotation Constancy Test: 15 trials of participants assessing bar angle (0, 90, 45, −45, 22, or −22 degrees relative to vertical) independent of head

tilt. Note: Allow participants to see each angle and tilt their head to left and right while viewing each angle before beginning the test.

  - Localization Trials: 10 trials of localizing a white dot on a black felt board with the vOICe device (5 separate positions). Record accuracy of reaching. Also record accuracy of random reaching for 10 trials (without vision, eyes closed), and with vision 10 trials (eyes open).

- Training Tasks:
  - Centering a white circle on the black-felt-covered table
  - Recognition of simple objects (such as distinguishing a square, triangle, and circle)
  - Distinguishing an "L" from a backward L, an upside-down L, and backward and upside-down L (*i.e.,* a 7)

Session 2 (1 hour) through Session 7 (1 hour)

- Assessments Tasks:
  - Shape Constancy Test: 20 trials of participants assessing bar length (1-5) independent of angle. Perform task on vOICe, and then with normal vision. Note: Allow participants to see the line lengths vertical and horizontal for each length before beginning the test **(allow head tilt).**
  - Rotation Constancy Test: 15 trials of participants assessing bar angle (0, 90, 45, –45, 22, or –22 degrees relative to vertical) independent of head

tilt. Note: Allow participants to see each angle and tilt their head to left and right while viewing each angle before beginning the test.

    - Localization Trials: 10 trials of localizing a white dot on a black felt board with the vOICe device (5 separate positions). Record accuracy of reaching. Also record accuracy of random reaching for 10 trials (without vision, eyes closed), and with vision 10 trials (eyes open).

- Training Tasks:
    - Work on shape constancy: Estimate length for just 90-degree lines, and then estimate length for just 45-degree lines (do not train on 0 or –45 degree angles) (Note: The training angles were limited to two angles for each participant, although the angles used across participants may have varied).
    - Work on rotation constancy: Estimate angles with the head only vertical, then estimate angles with head tilted to the left only, and estimate angles with head tilted to the right only.

Session 8 (1 hour) – Session 9 (1 hour)

- Assessments Tasks:
    - Shape Constancy Test: 20 trials of participants assessing bar length (1-5) independent of angle. Perform task on vOICe, and then with normal vision. Note: Allow participants to see the line lengths vertical and

horizontal for each length before beginning the test **(do NOT allow head tilt).**

- Rotation Constancy Test: 15 trials of participants assessing bar angle (0, 90, 45, –45, 22, or –22 degrees relative to vertical) independent of head tilt. Note: Allow participants to see each angle and tilt their head to left and right while viewing each angle before beginning the test.
- Localization Trials: 10 trials of localizing a white dot on a black felt board with the vOICe device (5 separate positions). Record accuracy of reaching. Also record accuracy of random reaching for 10 trials (without vision, eyes closed), and with vision 10 trials (eyes open).

- Training Tasks:
  - Work on shape constancy: Estimate length for just 90-degree lines, and then estimate length for just 45-degree lines (do not train on 0 or –45 degree angles)
  - Work on rotation constancy: Estimate angles with the head only vertical, then estimate angles with head tilted to the left only, and estimate angles with head tilted to the right only.

Session 10 (1.5 hour) (performed on iMac computer)

- Bouncing *vs*. Streaming
  - File: BounceVStream.m

- Moving Dot Experiment: Left-to-Right *vs*. Right-to-Left Rate Estimation Task (use headphones on table next to iMac computer)
    - File: vOICeVisIllExptMovDot2AFCQuarter.m
- Texture Experiment: Texture Interface V3 part II, and Texture V2 part I and part II
    - Files: TextureR3_partII.m (in Texture Interface V3), TextureR1_part1.m (in Texture V2), TextureR1_partII.m (in Texture V2)

APPENDIX C

POST-FMRI SCANNING QUESTIONNAIRE

All fMRI participants filled out a questionnaire following their final fMRI scanning session of the vOICe fMRI experiment. This questionnaire was used to better process the fMRI data, and to take into account factors such visualization.

vOICe fMRI Subject Questionnaire

Name: ____________________ Date: _______________

Thank you for performing the vOICe fMRI experiment. Please try to answer the following questions to the best of your memory.

1. I responded to questions in fMRI by pressing the button with:
Pre Scan (circle one): Left Hand Right Hand Both hands
Post Scan (circle one): Left Hand Right Hand Both hands

2. When localizing the dot in vOICe and with the images I:
Pre-training Scan (check one):
❑ Fixed my gaze on the center cross in all trials
❑ Tried to fix my gaze cross but may have wandered occasionally
❑ Did not try to fixate my gaze on the center cross
Post-training Scan (check one):
❑ Fixed my gaze on the center cross in all trials
❑ Tried to fix my gaze cross but may have wandered occasionally
❑ Did not try to fixate my gaze on the center cross

3. When localizing the dot in vOICe and with the images I:
Pre-training Scan (check one):
❑ Imagined pointing to the dot **after** the sound/image finished or disappeared
❑ Imagined pointing to the dot **before** the sound/image finished or disappeared
❑ Did not imagine pointing to the dot
Post-training Scan (check one):
❑ Imagined pointing to the dot **after** the sound/image finished or disappeared
❑ Imagined pointing to the dot **before** the sound/image finished or disappeared
❑ Did not imagine pointing to the dot

4. When listening for a pause in the noise (just following the auditory localization)
   Pre-training Scan (check all that apply):
   - ❑ I recognized that the sound was the vOICe device
   - ❑ I did not recognize that the sound was the vOICe device
   - ❑ I did not know what the vOICe device was

   Post-training Scan (check all that apply):
   - ❑ I recognized that the sound was the vOICe device
   - ❑ I did not recognize that the sound was the vOICe device
   - ❑ I did not know what the vOICe device was

5. When counting backwards in sets of 7:
   Pre-training Scan (check one):
   - ❑ The sound played distracted my counting significantly
   - ❑ The sound played distracted my counting somewhat
   - ❑ The sound played did not distract my counting at all

   Post-training Scan (check one):
   - ❑ The sound played distracted my counting significantly
   - ❑ The sound played distracted my counting somewhat
   - ❑ The sound played did not distract my counting at all

6. When counting backwards in sets of 7:
   Pre-training Scan (check one):
   - ❑ I started to imagine images of numbers
   - ❑ I counted in my head without imagining the shape or image of a number

   Post-training Scan (check one):
   - ❑ I started to imagine images of numbers
   - ❑ I counted in my head without imagining the shape or image of a number

7. When listening to the natural sounds with a pause in fMRI:
   Pre-training Scan (check one):
   - ❑ I started to imagine a visual scene (such as a beach)
   - ❑ I just listened to the sound for the pause with no “visual” imaginings

   Post-training Scan (check one):
   - ❑ I started to imagine a visual scene (such as a beach)
   - ❑ I just listened to the sound for the pause with no “visual” imaginings

APPENDIX D

COMPLETE FMRI DATA

Chapter 4 and Chapter 5 fMRI data that were truncated to the most significant 15 peaks of neural activation are presented in full in Appendix D. The tables in Appendix D include data from Tables 4.3 (Table A in Appendix D), Table 4.4B (Table B in Appendix D), and Table 5.4A (Table C in Appendix D).

Sighted Participants (*N* = 10)						
Region	BA	Side	*x*	*y*	*z*	p_{uncorr}
Star Trek Sound [Post – Pre]						
Insula	13	R	39	−46	19	0.000
Middle Temporal Gyrus	39	R	45	−55	7	0.001
- small volume-corrected peak						0.033*
Thalamus		R	6	−28	10	0.000
Caudate		R	21	−40	10	0.000
Thalamus		L	−6	−34	10	0.000
Middle Frontal Gyrus	6	R	33	−1	64	0.000
Caudate		R	3	5	4	0.000
Caudate		R	3	17	7	0.003
Precuneus	7	R	21	−49	46	0.000
Inferior Parietal Lobule	40	R	33	−43	46	0.001
Inferior Parietal Lobule	40	R	39	−55	46	0.004
Precentral Gyrus	6	L	−24	−16	70	0.001
Precentral Gyrus	6	L	−33	−7	67	0.005
Medial Frontal Gyrus	8	L	−12	38	34	0.001
Postcentral Gyrus	5	L	−24	−43	58	0.001
Paracentral Lobule	6	R	3	−34	70	0.002
Paracentral Lobule	4	R	9	−40	70	0.006
Lentiform Nucleus		L	−18	14	7	0.002
Caudate		L	−12	26	7	0.002
Precentral Gyrus	6	R	30	−19	70	0.003
Precentral Gyrus	4	R	42	−25	67	0.005
Superior Frontal Gyrus	8	L	−39	17	46	0.003
Middle Frontal Gyrus	8	L	−27	20	43	0.004

Sighted Participants ($N = 10$) Continued						
Region	**BA**	**Side**	***x***	***y***	***z*–**	p_{uncorr}
Superior Frontal Gyrus	6	L	–24	14	49	0.008

Table A: The Full Version of fMRI data: post – pre training familiar sounds sighted participants (Table 4.3). Complete imaging results for sighted participants when comparing post-vOICe-training scan and the pre-vOICe-training scan ($N = 10$). All regions were limited to $p < 0.009$ uncorrected and 10 voxel cluster threshold (p_{uncorr} refers to the peak level p_{uncorr}). The small volume correction was for a sphere of 10 millimeter radius around the cluster center, and the pvalue shown (indicated by asterisk, *i.e.*, *) is for the peak level FWE-corrected. Brodmann Area localization was performed on the talaraich client for nearest grey matter. Any clusters without nearest grey matter within +/– 5 mm are not included.

Late Blind Participants (N = 1) (RD)						
Region	**BA**	**Side**	***x***	***y***	***z***	p_{uncorr}
vOICe Noise Pause Detection [Post – Pre]						
Inferior Parietal Lobule	40	R	69	−25	25	0.000
- small volume-corrected peak						0.000*
Precentral Gryus	4	R	60	−7	22	0.000
Supermarginal Gyrus	40	R	51	−52	25	0.000
Inferior Parietal Lobule	40	L	−60	−28	28	0.000
Supermarginal Gyrus	40	L	−48	−49	34	0.000
Supermarginal Gyrus	40	L	−42	−37	34	0.000
Middle Temporal Gyrus	39	L	−45	−67	25	0.000
- small volume-corrected peak						0.000*
Caudate		R	21	−1	22	0.000
Caudate		R	18	8	22	0.000
Cingulate Gyrus	24	R	24	−10	34	0.000
Superior Frontal Gyrus	8	R	18	38	52	0.000
Middle Frontal Gyrus	8	R	24	38	40	0.003
Lingual Gyrus	19	R	33	−61	1	0.000
- small volume-corrected peak						0.009*
Caudate		L	−15	8	19	0.000
Caudate		L	−18	−16	22	0.002
Cingulate Gyrus	24	L	−18	−19	34	0.002
Superior Parietal Lobule	7	R	36	−64	61	0.000
Postcentral Gyrus	5	R	42	−46	67	0.000
Postcentral Gyrus	2	R	42	−37	67	0.000
Superior Frontal Gyrus	6	L	−18	−13	67	0.000
Medial Frontal Gyrus	6	L	−9	−10	61	0.002

Late Blind Participants (N = 1) (RD) Continued						
Region	**BA**	**Side**	***x***	***y***	***z*–**	p_{uncorr}
Superior Frontal Gyrus	6	L	−15	17	64	0.000
Precuneus	7	L	−12	−79	55	0.000
Postcentral Gyrus	5	L	−27	−40	67	0.001
Postcentral Gyrus	3	L	−30	−28	67	0.002
Lingual Gyrus	18	L	−30	−70	−8	0.001
Middle Occipital Gyrus	37	L	−36	−67	−2	0.001
Fusiform Gyrus	37	L	−36	−49	−14	0.001
Precuneus	7	L	−3	−46	52	0.002
Cingulate Gyrus	31	L	−6	−37	37	0.002
Cingulate Gyrus	31	L	0	−43	34	0.002
Cingulate Gyrus	31	R	3	−25	37	0.003
Precentral Gyrus	4	L	−54	−13	40	0.002
Superior Frontal Gyrus	9	L	−18	59	31	0.003
vOICe Distract Counting [Post – Pre]						
Middle Temporal Gyrus		R	51	−34	1	0.000
Superior Temporal Gyrus		R	63	−16	−2	0.000
Cuneus	17	R	12	−82	10	0.000
- small volume-corrected peak						0.000*
Posterior Lobe, Cerebellum		R	30	−64	−8	0.000
Posterior Lobe, Cerebellum		R	21	−76	−14	0.000
Insula	13	R	48	−22	25	0.000
Inferior Parietal Lobule	40	R	66	−37	28	0.000

Late Blind Participants (*N* = 1) (RD) Continued						
Region	**BA**	**Side**	***x***	***y***	***z***	p_{uncorr}
- small volume-corrected peak						0.000*
Inferior Parietal Lobule	40	R	39	−52	43	0.000
Middle Frontal Gyrus	8	L	−33	35	43	0.000
Middle Frontal Gyrus	8	L	−30	26	40	0.000
Middle Frontal Gyrus	9	L	−39	38	34	0.000
Inferior Parietal Lobule	40	L	−54	−28	25	0.000
Insula	13	L	−45	−19	19	0.000
Cingulate Gyrus	32	L	0	17	40	0.000
Medial Frontal Gyrus	6	L	−9	−4	58	0.000
Medial Frontal Gyrus	6	L	0	2	49	0.000
Superior Temporal Gyrus	22	L	−63	−7	4	0.000
- small volume-corrected peak						0.006*
Precuneus	7	L	−6	−61	43	0.000
Precuneus	7	L	−3	−79	43	0.000
Middle Frontal Gyrus	8	R	30	38	46	0.000
Superior Frontal Gyrus	9	R	39	44	34	0.002
Middle Frontal Gyrus	10	R	30	38	22	0.003
Middle Frontal Gyrus	46	R	39	26	22	0.000
Precentral Gyrus	6	R	60	−4	37	0.000
Precentral Gyrus	6	L	−51	−1	19	0.000
Middle Temporal Gyrus	39	L	−48	−58	25	0.000
Supramarginal Gyrus	40	L	−63	−49	25	0.001
Inferior Parietal Lobule	40	L	−45	−58	37	0.001
Superior Temporal Gyrus	22	L	−51	−49	7	0.000

Late Blind Participants (N = 1) (RD) Continued						
Region	**BA**	**Side**	x	y	z	p_{uncorr}
Claustrum		L	−27	−7	19	0.001
Caudate		L	−15	−22	19	0.001
Caudate		L	−15	−7	22	0.002
Superior Occipital Gyrus	19	R	33	−85	31	0.001
Precuneus	19	R	27	−82	43	0.002
Inferior Temporal Gyrus	20	L	−51	−55	−14	0.001
Medial Frontal Gyrus	8	L	0	53	46	0.001
Medial Temporal Gyrus	22	L	−57	−34	4	0.001
Cingulate Gyrus	31	L	0	−43	40	0.001
Precentral Gyrus	6	L	−48	−4	52	0.001
Anterior Cingulate	32	L	−18	32	19	0.001
Culmen		R	3	−49	−14	0.002
Culmen		L	−9	−43	−17	0.002
Superior Frontal Gyrus	8	R	15	44	52	0.002
Middle Frontal Gyrus	6	R	36	−4	46	0.002
Anterior Cingulate	32	L	−6	35	25	0.005
Medial Frontal Gyrus	9	L	−3	44	19	0.006
Precuneus	7	R	15	−61	37	0.005
Cuneus	19	R	15	−79	31	0.005
Precuneus	7	R	21	−67	31	0.006
Beach Pause Detection [Post – Pre]						
Precuneus	19	L	−24	−85	43	0.000
- small volume-corrected peak						0.000*
Supramarginal Gyrus	40	L	−60	−46	37	0.000

Late Blind Participants (N = 1) (RD) Continued						
Region	**BA**	**Side**	x	y	z	p_{uncorr}
- small volume-corrected peak						0.000*
Superior Occipital Gyrus	19	L	−36	−82	34	0.000
Middle Temporal Gyrus	39	R	45	−61	28	0.000
- small volume-corrected peak						0.001*
Inferior Parietal Lobule	40	R	69	−25	25	0.000
Precuneus	19	R	33	−79	34	0.000
Middle Frontal Gyrus	8	L	−45	17	49	0.000
Superior Frontal Gyrus	8	L	−27	44	40	0.000
Superior Frontal Gyrus	9	L	−18	59	34	0.005
Superior Frontal Gyrus	9	L	−27	56	34	0.008
Superior Frontal Gyrus	10	L	−42	50	25	0.000
Lingual Gyrus	19	L	−33	−67	−2	0.004
Star Trek Pause Detection [Post – Pre]						
Cuneus	17	R	9	−82	10	0.000
- small volume-corrected peak						0.000*
Lingual Gyrus	18	L	−15	−79	−5	0.000
- small volume-corrected peak						0.003*
Lingual Gyrus	18	R	18	−70	4	0.000
Superior Temporal Gyrus	39	R	48	−55	25	0.000
- small volume-corrected peak						0.000*
Inferior Parietal Lobule	40	R	69	−31	28	0.000
- small volume-corrected peak						0.000*
Postcentral Gyrus	2	R	45	−25	31	0.000
Middle Temporal Gyrus	39	L	−42	−61	25	0.000

Late Blind Participants (*N* = 1) (RD) Continued						
Region	**BA**	**Side**	***x***	***y***	***z***	p_{uncorr}
Inferior Parietal Lobule	40	L	−57	−28	25	0.000
Inferior Parietal Lobule	40	L	−48	−34	28	0.000
Precuneus	19	R	33	−79	34	0.001
- small volume-corrected peak						0.044*
Precuneus	7	L	−21	−79	49	0.002

Table B: The Full Version of fMRI data: post – pre training late blind participant (Table 4.4 B). Complete imaging results for a late blind participant (*N* = 1) when comparing post-vOICe-training scan and the pre-vOICe-training scan. All regions were limited to $p < 0.009$ uncorrected and 10 voxel cluster threshold (p_{uncorr} refers to the peak level p_{uncorr}). The small volume correction was for a sphere of 10 millimeter radius around the cluster center, and the pvalue shown (indicated by asterisk, *i.e.*, *) is for the peak level FWE-corrected. Brodmann Area localization was performed on the talaraich client for nearest grey matter. Any clusters without nearest grey matter within +/− 5 mm are not included.

Late Blind Participants (*N* = 1) (RD)						
Region	BA	Side	*x*	*y*	*z*	p_{uncorr}
vOICe Dot Post [Right – Left]						
No Activation						
vOICe Dot Post [Left – Right]						
Fusiform Gyrus	37	R	42	−55	−8	0.000
Claustrum			36	−22	−2	0.000
Fusiform Gyrus	19	R	42	−73	−11	0.000
Temporal Lobe	37	L	−42	−46	−8	0.000
Culmen		L	−18	−58	−8	0.000
Culmen		L	−21	−49	−11	0.000
Cuneus	18	R	15	−67	16	0.000
Posterior Cingulate	30	R	15	−52	13	0.000
Cuneus	18	R	12	−76	25	0.000
Middle Temporal Gyrus	39	R	51	−76	25	0.000
Middle Temporal Gyrus	39	R	57	−67	25	0.000
Middle Temporal Gyrus	39	R	60	−64	13	0.003
Middle Occipital Gyrus	18	L	−24	−82	−8	0.000
Thalamus		L	−3	−7	10	0.000
Lentiform Nucleus		L	−18	2	10	0.002
Inferior Frontal Gyrus	45	R	57	14	22	0.001
Middle Occipital Gyrus	19	L	−36	−70	13	0.001
Insula	13	R	39	−4	19	0.002
Middle Temporal Gyrus	21	L	−51	−31	−5	0.002
Claustrum		R	36	2	7	0.002
Inferior Frontal Gyrus	45	L	−57	17	19	0.003

Late Blind Participants ($N = 1$) (RD) Continued						
Region	BA	Side	x	y	z	p_{uncorr}
Lentiform Nucleus		R	18	5	10	0.005
Lentiform Nucleus		R	21	2	1	0.005

Table C. The Full Version of fMRI data: vOICe dot [Right – Left location] post-scan late blind participant (Table 5.4 A). Complete imaging results for a late blind participant when comparing the post-training left dot and the post-training right dot in vOICe ($N = 1$). All regions were limited to $p < 0.009$ uncorrected and 10 voxel cluster threshold. The small volume correction was for a sphere of 10 millimeter radius around the cluster center, and the pvalue shown (indicated by asterisk, *i.e.*, *) is for the peak level FWE-corrected. Brodmann Area localization was performed on the talaraich client for nearest grey matter. Any clusters without nearest grey matter within +/– 5 mm are not included.

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