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Mental Imagery Follows Similar Cortical Reorganization as Perception: Intra-Modal and Cross-Modal Plasticity in Congenitally Blind

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Abstract

Cortical plasticity in congenitally blind individuals leads to cross-modal activation of the visual cortex and may lead to superior perceptual processing in the intact sensory domains. Although mental imagery is often defined as a quasi-perceptual experience, it is unknown whether it follows similar cortical reorganization as perception in blind individuals. In this study, we show that auditory versus tactile perception evokes similar intra-modal discriminative patterns in congenitally blind compared with sighted participants. These results indicate that cortical plasticity following visual deprivation does not influence broad intra-modal organization of auditory and tactile perception as measured by our task. Furthermore, not only the blind, but also the sighted participants showed cross-modal discriminative patterns for perception modality in the visual cortex. During mental imagery, both groups showed similar decoding accuracies for imagery modality in the intra-modal primary sensory cortices. However, no cross-modal discriminative information for imagery modality was found in early visual cortex of blind participants, in contrast to the sighted participants. We did find evidence of cross-modal activation of higher visual areas in blind participants, including the representation of specific-imagined auditory features in visual area V4.

Key words: auditory, blindness, decoding, mental imagery, tactile

Introduction

From infancy to old age, each and every person is exposed to sensory inputs from different modalities, is engaged in thoughts and actions and experiences a wide variety of emotions. In the early stages of life, during development, extensive cortical remapping takes place in the brain. This developmental cortical plasticity often occurs during critical periods and is also experience-based. While increased exposure to certain sensory experiences during development shapes cortical plasticity, sensory deprivation has equally large effects on the functional architecture of the cortex (Hubel and Wiesel 1970; Hubel et al. 1976). Early research in blind individuals has shown that the function of cortical regions is not predefined and that, for example, the visual cortex can be recruited by other modalities (Wanet-Defalque et al. 1988). These findings challenge the notion that the sensory cortices are solely responsive to input from a single modality and have major consequences for understanding cross-modal plasticity in sensory systems for perception as well as in perception-related mental imagery skills.

In many studies about cortical plasticity in the congenitally blind, the assumption was that auditory and haptic perception is unimpaired and that normal or enhanced performance on perceptual tasks in these modalities might be expected. Why

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would one expect that blind individuals show enhanced performance on auditory and tactile tasks? In adult blind individuals, the cortical organization is not solely formed by developmental plasticity after visual deprivation, but also through practice-based learning. In fact, enhanced processing on auditory and tactile tasks by congenitally blind might be expected due to modality-specific practice and exposure—they rely on auditory and tactile perceptual information where sighted people rely on visual perception. For example, they may learn to explore the environment using a cane, learn to read Braille and focus more on auditory and haptic cues to interact with others and interpret the world around them. Research on cortical plasticity has shown that these behaviorally important experiences can cause dynamic remodeling of cortical representations, which go together with the progression of learning (e.g. Buonomano and Merzenich 1998). For example, Pascual-Leone and Torres (1993) showed that Braille readers have an enhanced representation in somatosensory cortex of their right index finger, which they used to read with, compared with nonbraille readers. This practice-based remodeling of cortical representations can take place during sensory-based learning in any sensory modality (Recanzone et al. 1993; Schneider et al. 2005a; 2005b; Jancke et al. 2009) and may also take place after mental practice (Herholz et al. 2008; Tartaglia et al. 2009; Plailly et al. 2012; de Borst et al. 2016). Representational remodeling could take place for many auditory and tactile tasks that congenitally blind people systematically perform, for example, pitch representations could be more detailed for tasks that they perform using audition, such as person identification, compared with sighted people that would use visual information. Their functional specialization might give rise to more detailed neural representations of relevant features (e.g. spectral properties) both within the perception and mental imagery domains, which in turn might lead to better differentiation of individual stimuli and stimulus classes. For example, earlier work by de Borst et al. (2016) showed that expertise in a specific modality (visual cinematographers vs. auditory sound designers) led to enhanced decoding of imagery modality in the regions of expertise (e.g. parietal/occipito-temporal cortex for cinematographers vs. auditory cortex for sound designers). However, due to the fact that blind people perform a broad range of tasks differently from sighted people and have inherently different experiences, we expect representational remodeling to occur across many areas of the cortex, unlike professional musicians that are trained in one specific task and show enhanced representations only in the relevant area.

In line with the assumptions of practice-based learning, several studies have found increased performance of blind participants on a variety of haptic tasks, including fine-grained tactile discrimination (Sunanto and Nakata 1998; Van Boven et al. 2000; Goldreich and Kanics 2003; Postma et al. 2007; Alary et al. 2008, 2009; Norman and Bartholomew 2011; Bauer et al. 2015). However, other studies have indicated the opposite: that early visual exposure in sighted individuals enhances performance on haptic tasks, while blind individuals show impaired performance—especially in tasks that relied on a spatial component (Bailes and Lambert 1986; Pasqualotto and Newell 2007; Postma et al. 2008; Gori et al. 2010). Yet, other studies found no evidence for differences in haptic perception performance between blind and sighted participants (Heller 1989b; Morrongiello et al. 1994; Gentaz and Hatwell 1998; Grant et al. 2000; Postma et al. 2007; Heller et al. 2008; Alary et al. 2009; Picard et al. 2010; Norman and Bartholomew 2011; Baumgartner et al. 2015; Bonino et al. 2015). Neuroimaging studies of haptic perception mainly found overlapping neural recruitment between congenitally blind and sighted participants, with the exception of the visual areas, which were more (extensively) activated in congenitally blind participants (Rosler et al. 1993; Roder et al. 1997; Ricciardi et al. 2007; Amedi et al. 2010; Bauer et al. 2015).

Similar results were found in the auditory domain, with a majority of studies showing enhanced auditory processing in blind individuals (Lessard et al. 1998; Gougoux et al. 2004; Voss et al. 2004; Focker et al. 2012; Voss and Zatorre 2012; Collignon et al. 2013; Lewald 2013; Jafari and Malayeri 2014; Kattner and Ellermeier 2014; Lerens and Renier 2014; Lerens et al. 2014; Cornell Karnekull et al. 2016; Nilsson and Schenkman 2016; Kolarik et al. 2017) and some studies reporting impaired performance on auditory tasks (Gori et al. 2014; Finocchietti et al. 2015; Menard et al. 2015; Cappagli and Gori 2016; Voss 2016), or no difference from sighted participants (Collignon et al. 2011, 2013; Voss and Zatorre 2012). These different results may depend on the specific task requirements (King 2014), or may reflect a trade-off between different auditory abilities (Voss et al. 2015). Moreover, neural differences in auditory processing between blind and sighted participants have been found (Schepers et al. 2012; Watkins et al. 2013; Jiang et al. 2014; Holig et al. 2014a; Coullon et al. 2015; Guerreiro et al. 2016; Murphy et al. 2016), where—similar to haptic processing—the visual cortex is more strongly involved in blind participants during auditory perception (Burton et al. 2003; Dietrich et al. 2013; Lewald and Getzmann 2013; Occelli et al. 2013; Watkins et al. 2013; Striem-Amit and Amedi 2014; Anurova et al. 2015; Lane et al. 2015; Tao et al. 2015). Enhanced performance of blind people on auditory tasks also seems to be related to differences in underlying anatomical changes, e.g. increased cortical thickness in auditory cortex, compared with sighted people (Voss and Zatorre 2012).

To summarize so far, it is evident that perceptual experiences, and lack thereof, have shaped the cortical organization in congenitally blind during periods of developmental and adult plasticity. The visual areas of blind individuals are recruited during a variety of tasks, including auditory and haptic perception and these activations seem to largely follow the general organization of the visual system, such as the division in a dorsal and ventral stream (Striem-Amit et al. 2012b) and the representation of categories (van den Hurk et al. 2017). However, for a phenomenon closely linked to perception, mental imagery, it is unknown how sensory deprivation and compensatory plasticity affect its cortical organization. In sighted individuals, it has been suggested that the representations that give rise to the experience of visual imagery are depictive in nature (e.g. Kosslyn et al. 1983). In support of this hypothesis, neuroimaging research has shown that visual mental imagery can reactivate the primary visual cortex in sighted individuals, which mainly seems to rely on the imagination of fine-grained details (Kosslyn et al. 1993, 1999; Klein et al. 2000; Ishai et al. 2002; Ganis et al. 2004; de Borst et al. 2012, 2016). In a similar vein, tactile imagery—the mental imagination of touch—can reactivate the primary somatosensory cortex (Schmidt et al. 2014; de Borst and de Gelder 2017). For auditory imagery, the imagination of sounds, it has also been shown that the auditory mental representations contain detailed information about auditory features, even if mainly the secondary and not the primary auditory cortex is activated during auditory imagery (Halpern and Zatorre 1999; Halpern et al. 2004; Bunzeck et al. 2005; Kleber et al. 2007; Daselaar et al. 2010; Zvyagintsev et al. 2013). Overall, this seems to suggest that the nature of mental imagery strongly depends on the modality in which it takes

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place, for example, tactile imagery is tactile in nature. However, does the cortical reorganization in congenitally blind follow similar principles for mental imagery as it does for perception? In other words, do mental imagery and perception rely on the same cortical mechanisms? The strong link between imagery and perception seems to suggest that they follow similar principles.

Most mental imagery research in congenitally blind has focused on the question whether visual imagery contributes to the execution of spatial tasks (a.o. Cornoldi et al. 1991; Aleman et al. 2001; Vanlierde et al. 2003; Vanlierde and Wanet-Defalque 2004; Noordzij et al. 2007). The neural basis of mental imagery within the intact auditory and haptic domains has been little researched in congenitally blind. The few studies that investigated haptic imagery focused on spatio-haptic tasks (Cattaneo et al. 2007; Bonino et al. 2008; Cornoldi et al. 2009; Occelli et al. 2014), or Braille reading (Heller 1989a; Buchel et al. 1998; Cohen et al. 2010; Striem-Amit et al. 2012a). Auditory working memory studies showed superior performance in early blind (Roder et al. 2001), which may be founded in superior encoding and consolidation (Stevens and Weaver 2005; Rokem and Ahissar 2009). Auditory imagery and working memory tasks during auditory perception, where the combined processing of mental imagery and perception is compared with perception of nonmeaningful sounds, or no sounds, seem to recruit visual cortex (De Volder et al. 2001; Gaab et al. 2006; Lewis et al. 2011; Park et al. 2011; Striem-Amit et al. 2012a; Watkins et al. 2012). However, in these studies it is unclear whether the visual cortex is responsive to meaningful versus nonmeaningful sounds, or to auditory imagery, as the memory processes were always measured during auditory perception. Thus, it is still unknown whether mental representations in the haptic and auditory domains follow a similar cortical reorganization as perception, for example, is the visual cortex of congenitally blind individuals functionally relevant for haptic and auditory imagery and do the somatosensory and auditory cortices show similar or enhanced processing during imagery?

In this study we addressed these questions by studying tactile and auditory perception and mental imagery in congenitally blind and sighted participants. Our experimental design allowed us to study perceptual and mental imagery processes separately, without contaminating the imagery data with a simultaneous percept in the same modality. We chose stimuli that are highly relevant for social communication in blind people: recognition of voice identity and emotion. We matched these auditory stimuli with tactile stimuli that represented the same 2 categories: recognition of body identity and emotion, so that we could investigate modality-specific representations (e.g. auditory vs. tactile perception, Fig. 2), as well as categorical representations across modalities (Supplementary Material). We associated the voices and bodies with each other in a training session (see Fig. 1). In order to also investigate representation of information on the individual stimulus level (within-category, Fig. 4), each category had 2 stimulus exemplars (e.g. identity 1 and identity 2). The tasks required processing on the level of primary as well as higher sensory cortices, including recognition and imagery of voice identity (Formisano et al. 2008), of voice emotion through pitch (Hari et al. 1984; Allen et al. 2017), and of body identity and body emotion through tactile exploration and surface feature/shape discrimination (Bodegard et al. 2000; Reed 2002; Reed et al. 2004; Simoes-Franklin et al. 2011). Moreover, the tasks involved features on which blind individuals generally have better performance (e.g. pitch perception: Gougoux et al. 2004; Focker et al. 2012; Voss and Zatorre 2012) (e.g. tactile discrimination: Sunanto and Nakata 1998; Van Boven et al. 2000; Goldreich and Kanics 2003; Alary et al. 2009; Norman and Bartholomew 2011; Bauer et al. 2015). We employed classification analyses to answer the following questions. Do the primary sensory cortices, including the visual cortex, differentiate between auditory and tactile perception in blind and sighted participants, and if so, do the blind show enhanced representations in the auditory and somatosensory cortex? We hypothesize, on the basis of existing evidence, that perception modality can be successfully predicted in all sensory cortices in the blind and sighted groups. As the participants rely on pitch perception during the auditory perception task and tactile discrimination during the tactile perception task, we hypothesize that the blind will have more detailed perceptual representations due to experience-based functional specialization, which may lead to higher classification accuracies in the primary auditory and somatosensory cortices. Secondly, we investigate whether the primary sensory cortices differentiate between auditory and tactile imagery in blind and sighted participants and if so, whether the blind show enhanced representations in auditory and somatosensory cortex. Moreover, we want to test in specific whether the visual cortex differentiates between auditory and tactile imagery. Again, given the strong link between imagery and perception, we expect that imagery modality can be successfully predicted in all sensory cortices in the blind and sighted groups, and that the blind will show higher classification accuracies in the primary auditory and somatosensory cortices due to more detailed mental representations on the basis of their experience in the auditory and tactile domains. We hypothesize that mental imagery representations follow perceptual representations and that imagery modality can be differentiated in early visual cortex. Our final research question focused on whether primary sensory cortices, in blind and sighted groups, represent specific imagery content (e.g. identity 1 vs. identity 2) that goes beyond category information (e.g. houses vs. faces). In the visual domain, the primary sensory cortex has been shown to represent specific-imagined content in sighted people, such as grating orientation (Harrison and Tong 2009). For the other sensory domains, it is still largely unknown whether top-down modulations during imagery can evoke content-specific representations.

Methods

The design of this study is identical to the design described in de Borst and de Gelder (2017), where we reported the results of 12 sighted participants. The current study focuses on 8 congenitally blind participants. In order to compare the results of the blind participants with the sighted in this paper, we also reported the results of 8 age- and gender-matched sighted control participants, which are a subset of the 12 sighted participants of de Borst and de Gelder (2017). The subset of sighted participants was chosen on the basis of gender- and age-matching (e.g. sighted participants with ages closest to those of the blind participants were selected, with an equal number of male and female participants).

Participants

Eight congenitally totally blind volunteers of Belgian and Danish nationality participated in this study (4 males, 4 females, mean age 39.3 years, range 27–48, see Table 1). The data from the congenitally blind participants were compared with a group of 8 age- and gender-matched sighted control participants (4 males, 4 females, mean age 33.4 years, range 26–52). The 2 groups were matched on education level: all participants

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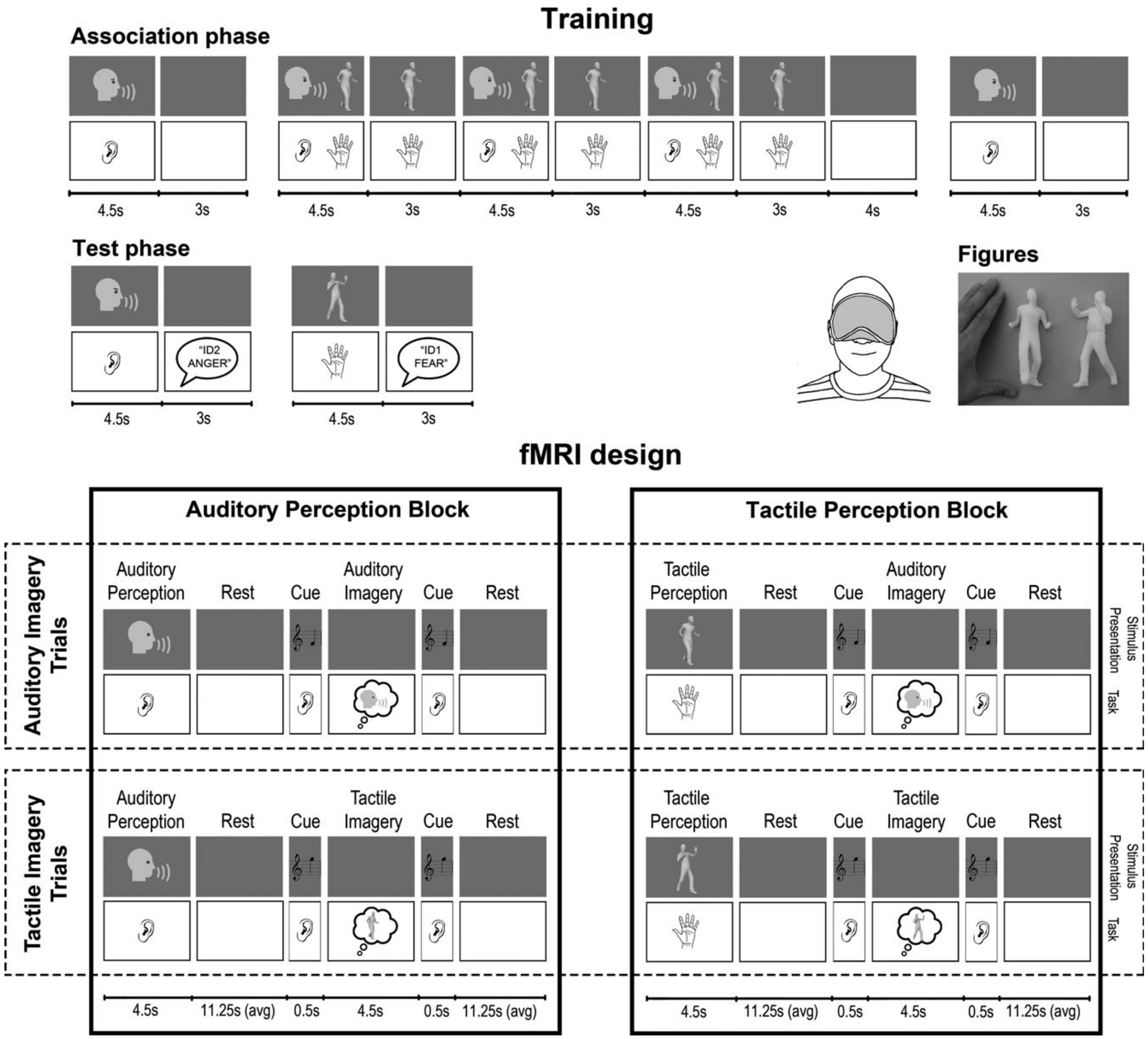

Figure 1. Task design. Top: Training phase, in which participants were first familiarized with the stimuli and associated the auditory stimuli with the tactile stimuli (e.g. ID 1 angry voice with ID 1 angry body). Subsequently, they were tested on how well they could identify the stimuli (separate for auditory and tactile stimuli). Bottom: fMRI design, in which the auditory perception block is visualized on the left and the tactile perception block is visualized on the right. In half of the trials the participants perform auditory imagery (top), while in the other half they perform tactile imagery (bottom), equally divided over both types of perception blocks. The (average) duration of each stimulus is indicated below in seconds.

completed higher education, with exception of one blind participant whose highest education level was high school. All participants gave their informed consent. Exclusion criteria were the institute's MRI safety criteria. The study was approved by the local ethical committee.

Stimuli

The stimuli consisted of 4 audio files of human voices, 2 audio files of tones and 4 3D-printed figures. The human voices were recorded from 2 male speakers, who were each expressing 2 emotions by wailing (fear) or growling (anger) without speech for 4.5 s. Additionally, Two 0.5 s tones of 400 Hz and 1200 Hz were used as cues. The 11-cm 3D figures were printed in-house using white thermoplastic material that was sanded afterwards to create a smooth surface. The 3D-printed figures consisted of 2 male identities expressing the same emotions as the auditory stimuli. The fearful emotion was expressed by the figure with open hands held in front of him, arching backwards, while the angry emotion was expressed with a forward bend and with fists clenched in front of him (Fig. 1). The identities were distinguishable by body shape, as one male was skinnier (ID 1), while the other one was plumper (ID 2), and their clothing was different.

Task

Before the start of the fMRI session, the participants were trained on associating the 4 different 3D-printed figures with the 4 different voices (Fig. 1 top and Supplementary Material). The seeing participants were blindfolded throughout the

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Table 1 Clinical and demographic details of congenitally blind participants.

Participant	Sex	Age	Handedness	Cause	Onset	Residual vision	Education
1	M	44	Right	LON	At birth	Minimal light sensitivity	Higher education
2	M	44	Right	ROP	At birth	None	High school
3	F	46	Right	ROP	At birth	Minimal light sensitivity	Higher education
4	F	32	Right	ROP	At birth	None	Higher education
5	F	39	Right	ROP	At birth	None	Higher education
6	F	34	Right	Unknown	At birth	None	Higher education
7	M	27	Right	ROP	At birth	Minimal light sensitivity	Higher education
8	M	48	Right	LON	At birth	Minimal light sensitivity	Higher education

LON, Leber's optic neuropathy; ROP, retinopathy of prematurity; M, male; F, female.

training. At the end of the training, all participants confirmed they could identify and imagine all individual stimuli correctly.

During fMRI measurements all participants were blindfolded, while keeping their eyes open. The participants were instructed to attend to the perceptual stimulus and keep it in mind. They were told that after a delay, they would hear either a low tone or a high tone. When hearing a low tone, they were instructed to imagine the audio of the stimulus that they just heard (after auditory perception) or imagine the audio that corresponded to the figure they just felt (after tactile perception). When hearing a high tone, they were instructed to imagine the figure that they just felt (after tactile perception), or imagine the figure that corresponded to the audio they just heard (after auditory perception). The slow-event related experiment was divided into 3 functional runs. In each run, the perception conditions were presented in a block (Fig. 1 bottom, auditory perception trials, and tactile perception trials). Within a block, trials consisted of the same perception condition followed by tactile or auditory imagery conditions. In the auditory perception block (Fig. 1 bottom left), each trial consisted of an affective voice (4.5 s), fixation (11.25 s average), start cue (0.5 s), imagery (4.5 s), end cue (0.5 s), and fixation (11.25 s average) (Fig. 1). The auditory stimulus indicated which identity and emotion the subject had to imagine. The start cue indicated the modality in which the subject had to imagine (low 400 Hz tone: auditory imagery, high 1200 Hz tone: tactile imagery). The tactile blocks (Fig. 1 bottom right) were identical to the auditory blocks, except for the first stimulus in each trial, which was tactile perception of the 3D figure. The 3D figures were manually presented to the participants' right hand by the experimenter, after which the participant could explore the figure with both hands. After 4.5 s, the figure was removed. Thus, independent of the perceptual modality, participants always performed trials of auditory (50%) and tactile imagery (50%) in each block. The participants always imagined the emotion and the identity of the stimulus simultaneously.

Design

The experiment contained 16 different experimental conditions: Auditory Perception of Fearful ID 1 (APF1), Auditory Perception of Fearful ID 2 (APF2), Auditory Perception of Angry ID 1 (APA1), Auditory Perception of Angry ID 2 (APA2), Auditory imagery of Fearful ID 1 (AIF1), Auditory Imagery of Fearful ID 2 (AIF2), Auditory Imagery of Angry ID 1 (AIA1), Auditory Imagery of Angry ID 2 (AIA2), Tactile Perception of Fearful ID 1 (TPF1), Tactile Perception of Fearful ID 2 (TPF2), Tactile Perception of Angry ID 1 (TPA1), Tactile Perception of Angry ID 2 (TPA2), Tactile Imagery of Fearful ID 1 (TIF1), Tactile Imagery of Fearful ID 2 (TIF2), Tactile Imagery of Angry ID 1 (TIA1), and Tactile Imagery of Angry ID 2 (TIA2). In the multivariate pattern analysis (MVPA) on imagery modality (auditory vs. tactile imagery), certain conditions were collapsed to create overarching conditions (i.e. their trials were analysed together). The condition Auditory Perception was created by collapsing conditions APF1, APF2, APA1, and APA2. Similarly, the conditions Auditory Imagery (AIF1, AIF2, AIA1, AIA2 collapsed), Tactile Perception (TPF1, TPF2, TPA1, TPA1 collapsed), and Tactile Imagery (TIF1, TIF2, TIA1, TIA2 collapsed) were created. In the other MVPA on imagery content (emotion and identity), the regular 16 conditions were used for analyses.

Each of the 3 functional runs contained 2 blocks. Each block consisted of 16 trials, making a total of 96 trials for the whole experiment. Each of the 16 conditions was presented 4 times per run (2 conditions per trial). The length of the fixation periods were 9 s, 10.5 s, 12 s, or 13.5 s. The lengths of the 2 fixation periods in each trial always added up to 22.5 s in order to keep the overall trial length identical. Therefore, fixation length was always assigned in pairs (9 s and 13.5 s, 13.5 s and 9 s, 10.5 s and 12 s, and 12 s and 10.5 s). The order of the trials, stimuli and the length of the fixation periods were pseudorandomized for each participant, so that every fixation length pair occurred an equal amount of times with every perceptual stimulus.

Data Acquisition

A 3 T Siemens MR scanner (MAGNETOM Prisma, Siemens Medical Systems, Erlangen, Germany) was used for imaging. Functional scans were acquired with a multiband Gradient Echo Echo-Planar Imaging sequence with a Repetition Time (TR) of 1500 ms and an Echo Time (TE) of 30 ms. For each functional run, 687 volumes were acquired comprising 57 slices (FoV = 200 × 200, matrix = 100 × 100, 2-mm isotropic voxels, inter slice time = 26 ms, flip angle = 77°, multiband acceleration factor = 3). Between the 2 functional runs, high-resolution T1-weighted structural images of the whole-brain were acquired with an MPRAGE with a TR of 2250 ms and a TE of 2.21, comprised of 192 slices (FoV = 256 × 256, matrix = 256 × 256, 1-mm isotropic voxels, flip angle = 9°).

Data Analyses

Functional MRI Preprocessing

The fMRI data were analyzed using fMRI analysis and visualization software BrainVoyager QX version 2.8.4 (Brain Innovation B.V., Maastricht, the Netherlands) and Matlab version R2013b, 8.2.0.701 (The Mathworks Inc., Natick, Massachusetts, USA). Functional data were 3D motion corrected (sinc interpolation),

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corrected for slice scan time differences and temporally filtered (high pass, GLM-Fourier, 2 sines/cosines). The data was not spatially smoothed to preserve all information for the multivariate analyses. The anatomical data were corrected for intensity inhomogeneity (Goebel et al. 2006) and transformed into Talairach space (Talairach and Tournoux 1988). The functional data were then aligned with the anatomical data and transformed into the same space, to create 4D volume time-courses (VTCs). The anatomical data were used for surface reconstruction (Goebel et al. 2006). For the group of blind participants, a cortex-based alignment procedure was carried out to match the subjects' cortices using curvature information (Goebel et al. 2002, 2004; Frost and Goebel 2012). However, the group-aligned averaged surface reconstruction of the blind participants was used for display purposes only in the group comparison of the classification of perception modality. The multivariate analyses were all performed in the volume space, not on the surface.

Region of Interest Definition

For the region of interest (ROI)-based classification analyses, we extracted probabilistic cyto-architectonic maps from the SPM Anatomy Toolbox (Version 2.1, Forschungszentrum Jülich GmbH; Eickhoff et al. 2005). We extracted all available subregions of primary auditory cortex (Te1.0, Te1.1, Te1.2) (Morosan et al. 2001), primary somatosensory cortex (Area 1, 2, 3a, 3b) (Geyer et al. 2000; Grefkes et al. 2001), primary motor cortex (Area 4a, 4p) (Geyer et al. 1996), and visual regions up to V5/MT (V1, V2, V3, V4, V5) (Amunts et al. 2000; Wilms et al. 2005; Malikovic et al. 2007). For details, see Supplementary Material and de Borst & de Gelder (2017). These anatomical ROIs were used as an input for the MVPA (see Multivariate Analyses).

Multivariate Analyses

For the prediction of perception modality (auditory vs. tactile perception), imagery modality (auditory vs. tactile imagery), and imagery content (imagery of ID 1 vs. ID 2 and imagery of fear vs. anger), we employed 2 types of MVPA. First, we performed the MVPA using a whole-brain search light mapping (WB-SLM) approach and subsequently we performed the analyses in anatomically defined ROIs using support vector machine (SVM) classification (ROI-SVM). The multivariate analyses were performed for each subject individually. The resulting prediction accuracies and voxel maps were subsequently used for calculating group results.

For the single trial estimation of the MVPA mean values were extracted in the perception intervals (2–8 volumes from onset) and the imagery intervals (2–8 volumes from onset) relative to baseline (–1 till 0 s before onset, % signal change) (Brainvoyager QX 2.8 MVPA Toolbox). For the WB-SLM analyses, a whole-brain mask of the group (from averaged VTC overall 8 subjects) was used to extract voxels. In cases where the 2 groups were compared, the set of voxels that was common to the 2 whole-brain masks was used for analyses. On the estimated trials, a SLM approach was applied to find the local patterns with the most discriminative voxels for the 2 classes (In-house Matlab scripts; Kriegeskorte et al. 2006). A leave-one-run-out strategy was then used for training and testing of the data using SVM classification. For the WB-SLM, a searchlight of 33 voxels with a radius of 3 (including the center) was used. The resulting search light maps were averaged over runs in each individual. We tested whether the average accuracy of a searchlight across subjects was significantly higher than chance. In order to determine the significance level, we considered the accuracies obtained in all the subjects and, using a resampling approach, computed the probability of obtaining the observation under the null hypothesis that the mean population accuracy is 50% (balanced two-class classification). Under the null hypothesis, the likelihood of the observations is symmetric around chance (if a subject is at chance level, 40% and 60% accuracies are equally likely), and it is therefore possible to build an empirical estimate of the null distribution by performing all the possible switches of the observed accuracies around chance (Good 2005; section 3.2.1). With $N = 8$ subjects, the total number of permutations was 2^8 (256) and it was therefore feasible to employ an exact permutation test. First, we subtracted the chance level accuracy (50%) from all observed accuracies (subjects * searchlights) to center them on zero. Then, we performed all possible switches of the observed accuracies around zero (2^8 = 256 permutations) and calculated an average accuracy across participants in each searchlight for every switch. These average accuracies were entered into the null distribution. We excluded the switches where none of the participants' accuracies were flipped and were all were flipped. The null distribution ultimately had 254 (number of permutations-2) * 169 806 (number of searchlights) values. The observed accuracies (with chance level subtracted) were tested against this null distribution. The correction for multiple comparisons was done using cluster threshold estimation based on the permutations: we set an initial uncorrected threshold of $\alpha = 0.01$ and, for each permutation, we tagged as significant those searchlights whose accuracy across subjects was larger than the $(1 - \alpha)$ quantile. For each permutation, we estimated the extent of the largest cluster of significant searchlights, and built a distribution of cluster sizes. Clusters of significant searchlights in the observed data larger than the 95% quantile of such distribution were considered significant, with $P < 0.05$.

For the between-group analyses, we restricted our focus to those searchlights that showed a significant difference from chance in at least one of the 2 groups, and we conducted a non-parametric one-way ANOVA (again via second level permutation tests) with group as a factor to highlight searchlights that showed a significant difference between the groups. For each permutation, we randomly reassigned the subjects across the 2 groups and computed an F-statistics. The empirical null distribution of F-statistics was then compared with the observed F-statistics in order to compute significance level. The possible number of permutations (i.e. group reassignments) was of several orders of magnitude larger than in the previous case, and we therefore employed random Monte Carlo permutations with $N = 1000$. We corrected for multiple comparisons using False Discovery Rate (FDR) correction with $P < 0.05$ (Benjamini and Hochberg 1995). The significant searchlights of the within-group analyses of perception-trained classification of perception modality in the blind and sighted participants are shown in Fig. 2A. We found no significant between-group searchlights. The WB-SLM within-group analyses of imagery-trained classification of imagery modality and imagery content did not yield significant results in the blind group and therefore no WB-SLM between-group analyses were performed for imagery modality and imagery content. The WB-SLM within-group results of imagery modality classification were significant in the sighted and are shown in Supplementary Fig. S2.

For the ROI-SVM classification, the same single trial estimations of the MVPA mean values in the perception and imagery intervals were used as during the WB-SLM analyses. The voxels

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were extracted within each ROI (see section "Region of Interest Definition"). On the estimated trials, a ROI-based approach was applied to discriminate response patterns within specific brain regions. A leave-one-run-out strategy was used for training and testing of the data using SVM classification. A single classification accuracy was obtained for each region per subject and run. These accuracies were then averaged over runs. We tested whether the average accuracy of a region across subjects was significantly higher than chance. Using the above-described methods (but using "subjects by regions" instead of "subjects by voxels"), we tested the accuracies against an empirical null distribution and corrected for multiple comparisons using FDR correction with $P < 0.05$. The results of the ROI-SVM analyses of perception modality (average accuracies and standard error) in the blind group are shown in Fig. 2*B* and in the sighted group in Fig. 2*C*. The results of the ROI-SVM analyses of imagery modality (average accuracies and standard error) in the blind group are shown in Fig. 3*A* and in the sighted group in Fig. 3*B*. The results of the ROI-SVM analyses of imagery content in the blind group are shown in Fig. 4*A*, and in the sighted group in Figs 4*B*–*D*.

For the between-group analyses, we again conducted a nonparametric one-way ANOVA (via second level permutation tests) with group as a factor to highlight regions that showed a significant difference between the groups. For each permutation, we randomly reassigned the subjects across the 2 groups and computed an *F*-statistics. The empirical null distribution of *F*-statistics was then compared with the observed *F*-statistics in order to compute the significance level. We employed random Monte Carlo permutations with $N = 1000$ and corrected for multiple comparisons using FDR correction with $P < 0.05$.

Results

Classification of Perception Modality in Blind and Sighted

First, we tested whether we could successfully discriminate tactile and auditory perception from local patterns in the brain, using a searchlight mapping approach, and from the primary sensory cortices, using a ROI-SVM approach. These analyses were performed to assess whether the absence of visual experience has an influence on the neural representations in the intact perception modalities.

Whole-Brain Searchlight Mapping Analysis

We performed classification of auditory versus tactile perception using a perception-trained classifier and a leave-one-run-out cross-validation approach. We found that we could successfully discriminate the auditory and tactile modalities during the perception period across most of the cortex in both the blind (Fig. 2*A*, yellow, mean decoding accuracy = 66%, $P_{\mathrm{CORR}} < 0.05$) and the sighted participants (Fig. 2*A*, red, mean decoding accuracy = 69%, $P_{\mathrm{CORR}} < 0.05$). In the blind participants searchlights that contained perception modality information covered most of the parietal, visual, temporal, and right frontal cortex. In the left frontal cortex, perception modality information pertained to the medial anterior portion. In the sighted participants searchlights that contained perception modality information covered most of the parietal, visual, and right temporal cortex. The left superior temporal sulcus (STS) contained little perception modality information on the group level in the sighted participants. In the frontal cortex, the perception modality information mainly pertained to the posterior portions (premotor cortex). Subsequently, we tested whether the classification accuracies for perception modality across the brain were different for blind versus sighted participants. There were no voxels that showed significant differences between groups for the classification of perception modality (FDR > 0.05). This means that although certain regions, such as the right prefrontal cortex, had decoding accuracies that were significantly above chance in one group (e.g. 57%), but not in the other (e.g. 53%), the decoding accuracies in these regions were not significantly different between groups (e.g. 57% was not significantly larger than 53%). Our findings are largely in line with earlier research that showed similar patterns of brain activity in blind and sighted participants during tactile perception (Rosler et al. 1993; Roder et al. 1997; Ricciardi et al. 2007; Amedi et al. 2010; Bauer et al. 2015), but contrast to the neural differences found between blind and sighted participants during auditory perception (Schepers et al. 2012; Watkins et al. 2013; Jiang et al. 2014; Holig et al. 2014a; Coullon et al. 2015; Guerreiro et al. 2016; Murphy et al. 2016). The WB-SLM results for perception modality were found in the absence of any univariate effects in the 2 groups, but we did find univariate differences between perception modalities in several ROIs (see Supplementary Fig. S3).

ROI-SVM Classification

Subsequently, we tested whether the primary sensory cortices of blind and sighted participants differentiate between auditory and tactile perception by performing ROI-SVM classification analyses on the basis of anatomical probability maps (see Fig. 2*B*,*C* and Methods). We were able to predict perception modality in all primary sensory cortices, including primary visual cortex, in both the blind and sighted groups. Overall, classification accuracies in the blind participants were lower than in the sighted, although not statistically different from the sighted participants (with exception of primary motor area 4p). Recent research by van der Hurk et al. (2017) showed that double the amount of trials may be needed in blind participants to obtain classification accuracies that are similar to sighted participants. However, Fig. 2*B*,*C* shows that the relative proportions of accuracies between regions were remarkably similar between the blind and sighted. In the auditory cortex of blind and sighted participants, we were able to successfully decode perception modality in areas Te1.0 (blind: accuracy 88%, $P[\mathrm{FDR}] < 0.01$; sighted: accuracy 97%, $P[\mathrm{FDR}] < 0.005$), Te1.1 (blind: accuracy 80%, $P[\mathrm{FDR}] < 0.01$; sighted: accuracy 93%, $P[\mathrm{FDR}] < 0.005$), and Te1.2 (blind: accuracy 88%, $P[\mathrm{FDR}] < 0.01$; sighted: accuracy 96%, $P[\mathrm{FDR}] < 0.005$). In the primary somatosensory cortex of blind and sighted participants, we were able to successfully decode perception modality in area 1 (blind: accuracy 72%, $P[\mathrm{FDR}] < 0.01$; sighted: accuracy 90%, $P[\mathrm{FDR}] < 0.005$), area 2 (blind: accuracy 80%, $P[\mathrm{FDR}] < 0.01$; sighted: accuracy 94%, $P[\mathrm{FDR}] < 0.005$), area 3a (blind: accuracy 88%, $P[\mathrm{FDR}] < 0.01$; sighted: accuracy 95%, $P[\mathrm{FDR}] < 0.005$), and area 3b (blind: accuracy 79%, $P[\mathrm{FDR}] < 0.01$; sighted: accuracy 93%, $P[\mathrm{FDR}] < 0.005$). Also in primary motor cortex we could decode perception modality in all regions of both groups: area 4a (blind: accuracy 80%, $P[\mathrm{FDR}] < 0.01$; sighted: accuracy 92%, $P[\mathrm{FDR}] < 0.005$) and area 4p (blind: accuracy 85%, $P[\mathrm{FDR}] < 0.01$; sighted: accuracy 95%, $P[\mathrm{FDR}] < 0.005$). Next to the primary sensory cortices that were used during auditory and tactile perception, we could also successfully decode perception modality in the visual cortex, both in the blind and sighted participants. Although classification accuracies were lower than in the other primary sensory cortices, classification was successful in all visual areas, including V1 (blind: accuracy 62%, $P[\mathrm{FDR}] < 0.05$; sighted: accuracy 69%, $P[\mathrm{FDR}] < 0.005$), V2 (blind: accuracy 59%, $P[\mathrm{FDR}] < 0.05$;

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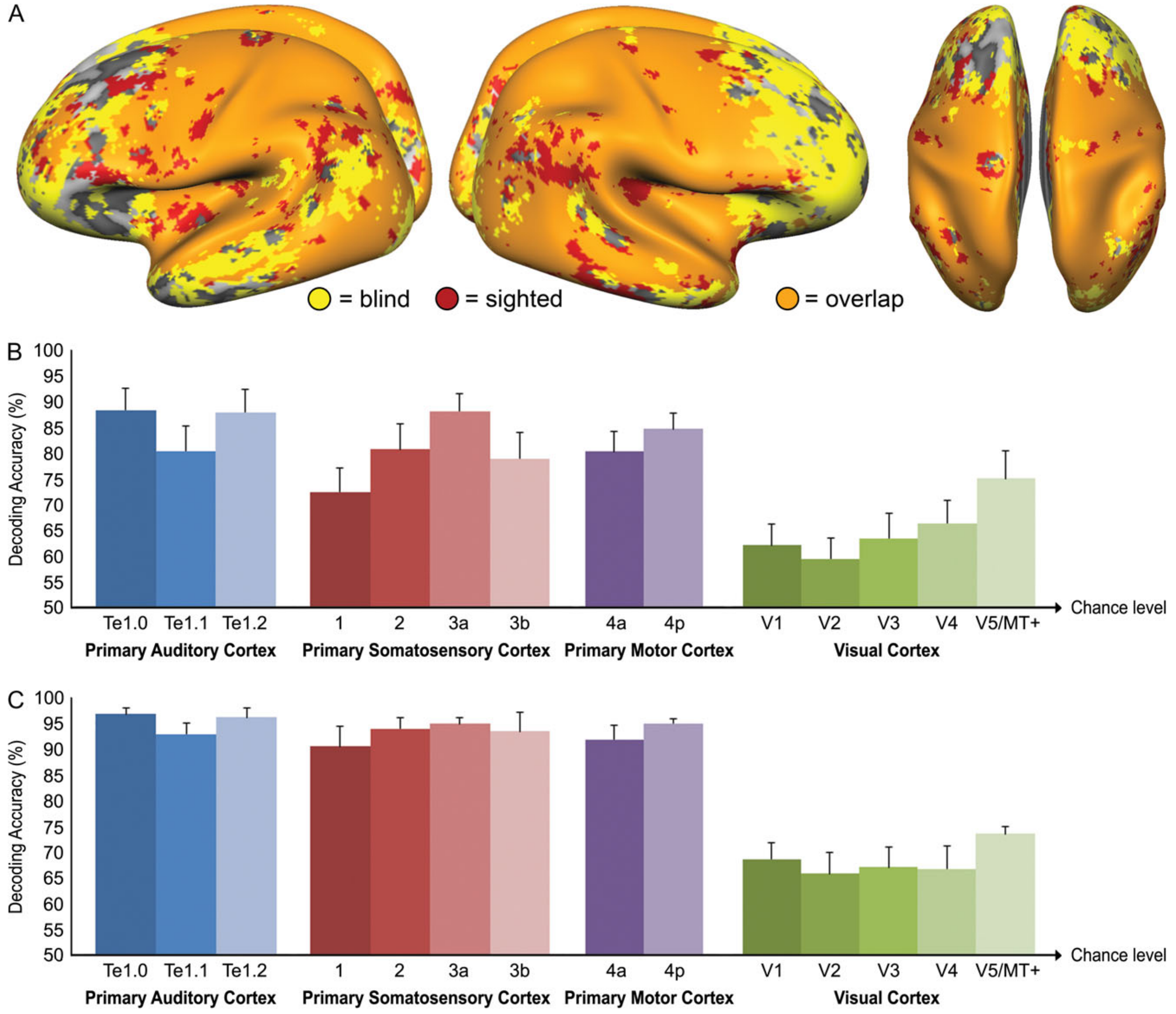

Figure 2. Classification of auditory versus tactile perception. (*A*) Searchlights that contain significant information about perception modality on the group level (*P*[corrected] < 0.05) are color-coded in yellow for the group of blind participants and in red for the sighted participants. Orange indicates overlapping searchlights that were significant in both groups. The results are displayed on the group-aligned inflated average surface of the blind participants. (*B*) The classification accuracies and standard errors of anatomical regions that contain significant information (*P*[corrected] < 0.05) about perception modality on the group level in blind participants are shown. (*C*) The classification accuracies and standard errors of anatomical regions that contain significant information (*P*[corrected] < 0.05) about perception modality on the group level in sighted participants are shown.

sighted: accuracy 66%, *P*[FDR] < 0.005), V3 (blind: accuracy 63%, *P*[FDR] < 0.01; sighted: accuracy 67%, *P*[FDR] < 0.005), V4 (blind: accuracy 66%, *P*[FDR] < 0.01; sighted: accuracy 67%, *P*[FDR] < 0.005) and V5/MT+ (blind: accuracy 75%, *P*[FDR] < 0.01; sighted: accuracy 74%, *P*[FDR] < 0.005).

We verified that we were decoding perception modality and not the low-level differences between 2 arbitrary sets of stimuli, by showing that decoding was not successful when using 2 arbitrary categories (see Supplementary Material, "Verification analyses for perception modality results") and by showing that decoding was successful when using different stimulus sets for training and testing (Supplementary Fig. S1). We also found univariate differences between perception conditions in primary auditory, somatosensory and motor cortices in both groups using ROI-GLM analyses (Supplementary Fig. S2).

A significant group difference in classification accuracies for the prediction of perception modality was found in primary motor cortex area 4p (*P*[FDR] = 0.01), with higher accuracies for the sighted than the blind participants. Trends were found in primary auditory cortex areas Te1.0 and Te1.1 (*P*[FDR] < 0.1), primary somatosensory cortex areas 1, 2, and 3b (*P*[FDR] < 0.1) and primary motor cortex area 4a (*P*[FDR] < 0.1).

Classification of Imagery Modality in Blind and Sighted

Next, we investigated whether mental imagery in blind participants recruited the 2 intact perceptual modalities, auditory and tactile, in a similar manner as in sighted participants, or whether a lack of visual experience had an influence on the neural basis of their mental imagery. The blind participants did

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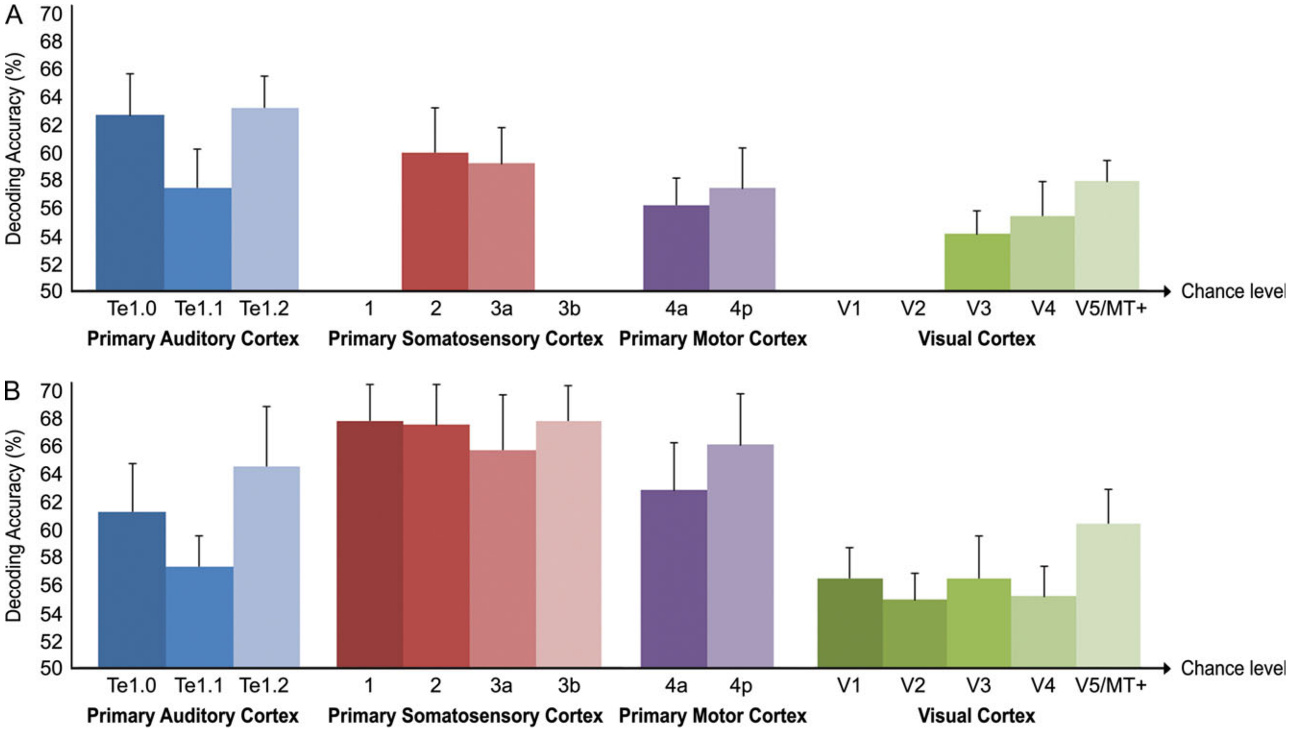

Figure 3. Classification of auditory versus tactile imagery. (*A*) Classification accuracies and standard errors of anatomical regions that contain significant information (*P*[corrected] < 0.05) about imagery modality on the group level in blind participants are shown. (*B*) Classification accuracies and standard errors of anatomical regions that contain significant information (*P*[corrected] < 0.05) about imagery modality on the group level in sighted participants are shown.

not show any significant group results for the searchlight classification analysis of imagery modality. Therefore, we only present the ROI-SVM classification results here (Fig. 3). In the sighted participants, we could successfully decode imagery modality using searchlight analyses (see Supplementary Material [$N = 8$] and de Borst and de Gelder (2017) [$N = 12$]). No whole-brain univariate differences between imagery conditions were found in the 2 groups, but we did find univariate ROI-based differences in several areas of the primary auditory and somatosensory cortices (see Supplementary Fig. S4).

ROI-SVM Classification

In the auditory cortex of blind and sighted participants (Fig. 3), we were able to successfully decode imagery modality in areas Te1.0 (blind: accuracy 63%, *P*[FDR] < 0.05; sighted: accuracy 61%, *P*[FDR] < 0.05), Te1.1 (blind: accuracy 57%, *P*[FDR] < 0.05; sighted: accuracy 57%, *P*[FDR] < 0.05), and Te1.2 (blind: accuracy 63%, *P*[FDR] < 0.05; sighted: accuracy 64%, *P*[FDR] < 0.05). In the primary somatosensory cortex of blind and sighted participants, we were able to successfully decode imagery modality in area 2 (blind: accuracy 60%, *P*[FDR] < 0.05; sighted: accuracy 67%, *P*[FDR] < 0.01), area 3a (blind: accuracy 59%, *P*[FDR] < 0.01; sighted: accuracy 66%, *P*[FDR] < 0.05). In the sighted group, we were additionally able to decode imagery modality in primary somatosensory area 1 (accuracy 68%, *P*[FDR] < 0.01) and area 3b (accuracy 68%, *P*[FDR] < 0.01), but in the blind participants decoding accuracies were not significantly above chance (area 1: accuracy 56%, *P*[FDR] = 0.0549; area 3b: accuracy 55%, *P*[FDR] = 0.0732). In primary motor cortex, we could decode perception modality in all regions in the blind and sighted participants: area 4a (blind: accuracy 56%, *P*[FDR] < 0.05; sighted: accuracy 63%, *P*[FDR] < 0.01) and area 4p (blind: accuracy 57%, *P*[FDR] < 0.05; sighted: accuracy 66%, *P*[FDR] < 0.01).

Next to the primary sensory cortices that were used during auditory and tactile perception, we could also successfully decode imagery modality in the visual cortex, for some of the regions in the blind and for all of the regions in the sighted participants. Classification was successful in both blind and sighted participants in V3 (blind: accuracy 54%, *P*[FDR] < 0.05; sighted: accuracy 56%, *P*[FDR] < 0.05), V4 (blind: accuracy 55%, *P*[FDR] < 0.05; sighted: accuracy 55%, *P*[FDR] < 0.05) and V5/MT+ (blind: accuracy 58%, *P*[FDR] < 0.05; sighted: accuracy 60%, *P*[FDR] < 0.01). Additionally, in sighted participants imagery modality could be decoded from V1 (accuracy 56%, *P*[FDR] < 0.01) and V2 (accuracy 55%, *P*[FDR] < 0.05), while in blind participants decoding accuracies were not significantly above chance (V1: accuracy 51%, *P*[FDR] = 0.2745; V2: accuracy 52%, *P*[FDR] < 0.2618).

We tested for significant group differences in classification accuracies for the prediction of imagery modality and found no significant differences between groups. A trend was found in the primary somatosensory cortex area 1 (*P*[FDR] < 0.1).

Classification of Imagery Content in Blind and Sighted

Lastly, we addressed our final research question by testing whether we could successfully discriminate imagery content, for example, 2 imagined stimulus emotions or 2 imagined stimulus identities, from local patterns in the brain in the blind and sighted groups. The blind and sighted participants did not show any significant group results for the searchlight classification analysis of imagery content. Therefore, we only present the ROI-SVM classification results here (Fig. 4).

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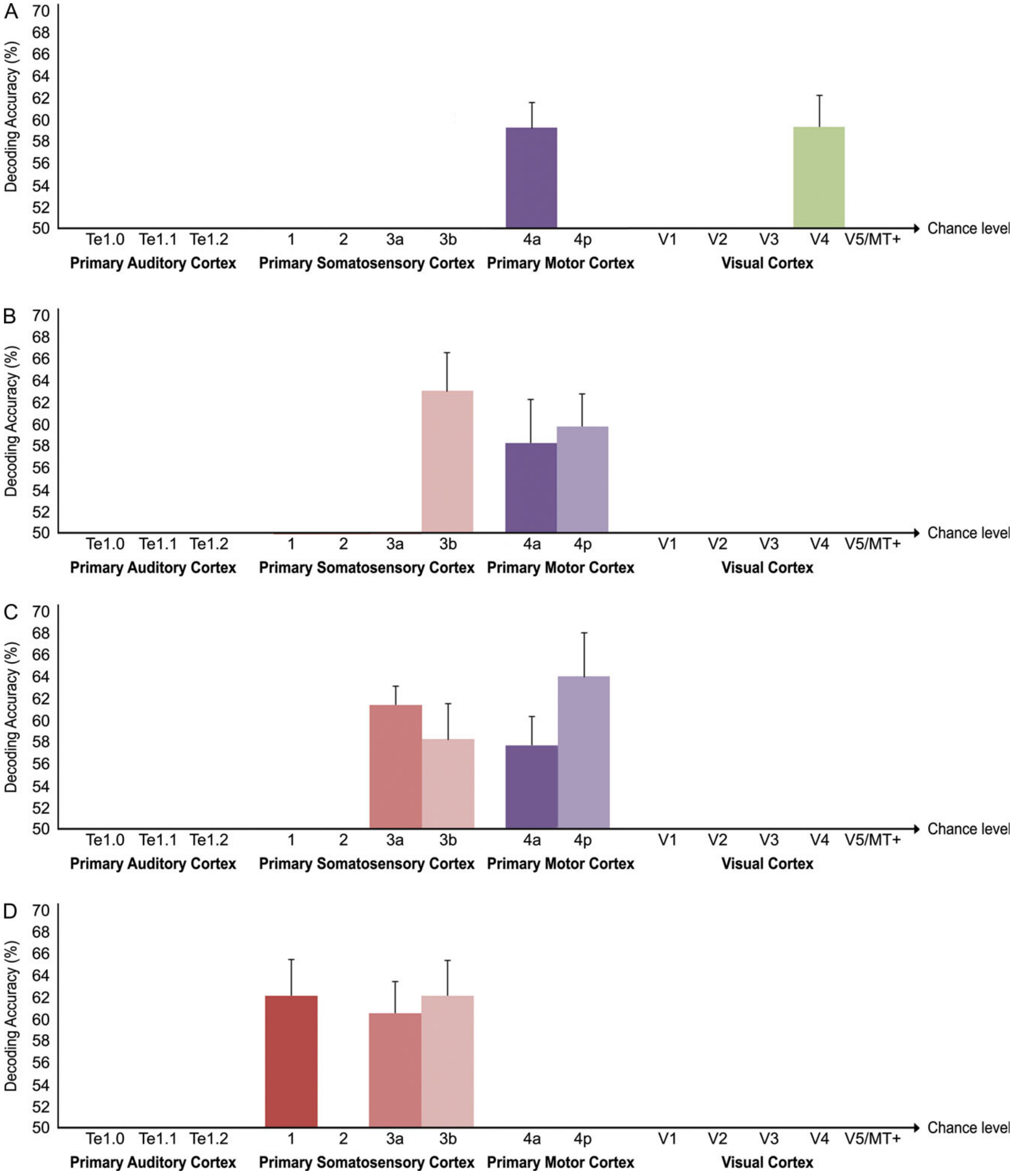

Figure 4. Classification of imagery content. (*A*) Classification accuracies and standard errors of anatomical regions that contain significant information (*P*[corrected] < 0.05) about auditory imagery of angry ID 1 versus ID 2 on the group level in blind participants are shown. (*B*) Classification accuracies and standard errors of anatomical regions that contain significant information (*P*[corrected] < 0.05) about auditory imagery of fearful ID 1 versus ID 2 on the group level in sighted participants are shown. (*C*) Classification accuracies and standard errors of anatomical regions that contain significant information (*P*[corrected] < 0.05) about auditory imagery of fearful versus angry ID 1 on the group level in sighted participants are shown. (*D*) Classification accuracies and standard errors of anatomical regions that contain significant information (*P*[corrected] < 0.05) about auditory imagery of fearful versus angry ID 2 on the group level in sighted participants are shown.

ROI-SVM Classification

In blind participants, we were able to successfully decode auditory imagery content (Fig. 4A). Specifically, auditory imagery of angry identity 1 versus identity 2 could be predicted from the primary motor cortex (4a: accuracy 59%, *P*[FDR] < 0.05) and V4 (accuracy 59%, *P*[FDR] < 0.05). The other auditory imagery

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content (fearful ID 1 vs. ID 2, ID 1 fear vs. anger, ID 2 fear vs. anger) and the tactile imagery content could not be decoded from the primary sensory cortices of the blind participants.

In sighted participants, we were able to successfully decode auditory imagery content as well. Auditory imagery of fearful identity 1 versus identity 2 (Fig. 4*B*) could be predicted from primary somatosensory cortex (3b: accuracy 63%, $P[\text{FDR}] < 0.05$) and primary motor cortex (4a: accuracy 58%, $P[\text{FDR}] < 0.05$; 4p: accuracy 60%, $P[\text{FDR}] < 0.05$). Next to imagined identity, we could also predict imagined emotion from the brain activity of sighted participants. Auditory imagery of angry versus fearful identity 1 (Fig. 4*C*) could be decoded from primary somatosensory cortex (3a: accuracy 61%, $P[\text{FDR}] < 0.05$; 3b: accuracy 58%, $P[\text{FDR}] < 0.05$) and primary motor cortex (4a: accuracy 58%, $P[\text{FDR}] < 0.05$; 4p: accuracy 64%, $P[\text{FDR}] < 0.05$). Auditory imagery of angry versus fearful identity 2 (Fig. 4*D*) could be decoded from primary somatosensory cortex (1: accuracy 62%, $P[\text{FDR}] < 0.05$; 3a: accuracy 60%, $P[\text{FDR}] < 0.05$; 3b: accuracy 62%, $P[\text{FDR}] < 0.05$). The auditory imagery of angry identity 1 versus identity 2 and all tactile imagery content could not be decoded successfully from the primary sensory cortices of the sighted participants.

Discussion

Our first goal was to find support for the hypothesis that primary sensory cortices, including primary visual cortex, differentiate between auditory and tactile perception in congenitally blind participants and that the underlying representations are more detailed (i.e. higher classification accuracies) than in the sighted group. Secondly, we examined the hypothesis that mental representations in congenitally blind follow perceptual representations such that imagery modality can be differentiated in primary sensory cortices, including early visual cortex, possibly with higher accuracies than in the sighted group. Finally, we tested whether primary sensory cortices in congenitally blind participants represent specific imagery content.

Representations of Perception Modality

We first investigated whether the primary sensory cortices differentiate between auditory and tactile perception in blind and sighted participants. Our results showed that the classification of auditory versus tactile perception was successful in all primary sensory cortices in both the blind and the sighted groups on the whole-brain level, as well as in the ROI analyses. Moreover, the whole-brain analyses indicated that the regions that contained information about perception modality far exceeded the primary sensory cortices. The perception modality representations extended from the primary sensory cortices to the association cortices, including the dorsal and ventral pathways, premotor cortex, supramarginal gyrus, and especially for the blind, the prefrontal cortex.

Congenitally-blind individuals may have additional expertise in the auditory and tactile domains and previous literature reported enhanced and more efficient haptic and auditory processing in the blind (see Introduction). Therefore, we expected that blind individuals would have more detailed perceptual representations of the auditory and tactile content, leading to more differentiated activation patterns and higher classification accuracies in the auditory and somatosensory cortex. Our results show the opposite effect. On the whole-brain level, we found that the perception modality information patterns were very similar for blind and sighted participants. We found no significant differences between the 2 groups, although in several regions one of the 2 groups showed decoding accuracies above chance, while the other did not (e.g. right prefrontal cortex in blind group). The ROI-SVM analyses showed that classification accuracies were significantly lower for the blind group in primary motor cortex area 4p, and the accuracies for primary auditory cortex areas Te1.0 and Te1.1, primary somatosensory cortex areas 1, 2, and 3b and primary motor cortex area 4a were around 10% lower for the blind than the sighted participants. This indicates that perception modality was not better differentiated in primary sensory cortices in the blind than the sighted. Even the relative proportions of accuracies between subregions of the primary sensory cortices were very similar between the sighted and blind, for example, both showed higher accuracies for primary motor area 4p than 4a, both showed higher accuracies for primary auditory cortex Te1.0 and Te1.2 compared with Te1.1. Although these findings contrast behavioral studies, they are in line with recent multivariate neuroimaging research in early blind. Jiang et al. (2014) showed that auditory motion in blind participants could be successfully decoded from MT+, but not from auditory cortex. Van den Hurk et al. (2017) showed that decoding accuracies for the classification of auditory object categories were lower for blind compared with sighted participants in auditory cortex. Overall, they also showed that for blind participants double the amount of trials were necessary to obtain classification accuracies that were similar to the sighted participants. Our results indicate that perceptual selectivity in the primary sensory cortices develops similarly with or without visual experience. These results are further confirmed by additional analyses, which indicate that the perception modality results are generalizable across different stimuli in both groups (Supplementary Fig. S1). Although representations of perception modality were comparable in the primary sensory cortices of the blind and sighted participants, the results of the whole-brain perception modality classification hint at possible differential processing in other parts of the blind cortex. Although not statistically different between groups, perception modality classification was significantly above chance in a large section of the right prefrontal cortex of the blind participants. This may indicate that blind participants use cognitive or attentional resources differently in the 2 perception conditions.

The ROI-SVM results further showed that perception modality could be decoded from cross-modal activity in the primary visual cortex and V2–V5 in both the blind and sighted groups, consistent with our hypothesis that the visual cortex would be recruited during auditory and tactile perception by the blind participants. Earlier research has shown that functional reorganization of the visual cortex after visual deprivation makes it responsive to a large variety of haptic and auditory tasks (Rosler et al. 1993; Roder et al. 1997; Burton et al. 2003; Ricciardi et al. 2007; Amedi et al. 2010; Dietrich et al. 2013; Lewald and Getzmann 2013; Occelli et al. 2013; Watkins et al. 2013; Striem-Amit and Amedi 2014; Anurova et al. 2015; Bauer et al. 2015; Lane et al. 2015; Tao et al. 2015). Interestingly, in line with those findings, our results also indicate that auditory and tactile modalities can be differentiated in early and extrastriate visual cortex, showing that they do not activate visual cortex in a similar manner. Additionally, we found that the sighted participants also showed differentiated cross-modal activation for auditory versus tactile perception in the visual cortex. Indeed, there is evidence of responsivity of the sensory cortices to other modalities in people with no deficits in sensory perception and not only in individuals where sensory deprivation has led to functional reorganization (Sathian and Lacey 2007; Liang et al.

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2013). For example, visual areas respond to specific auditory stimuli, including natural sounds in early visual cortex (Vetter et al. 2014), large nonmovable object sounds in parahippocampal place area (He et al. 2013), voices in fusiform gyrus (Holig et al. 2014b), and auditory motion (as well as haptic motion) in MT+ (Ricciardi et al. 2007; Strnad et al. 2013). All in all there are many examples of cross-modal activations in regions that are typically associated with intra-modal responses. It remains unclear whether these activations occur due to mental imagery processes during perception or due to feedback connections from the other sensory cortices. In our study, the perceptual representations in the blind participants are not based on visual imagery and are more likely a result of functional reorganization and/or feedback connections. As we found no differences between groups, it is difficult to say whether in the sighted group successful discrimination of perception modalities relied on feedback connections, or visual imagery. It may have been the case that visual imagery played a bigger role during tactile than auditory perception in the sighted individuals in our task (e.g. visualizing the figure during touch), because visual imagery could support the integration of the different (body) parts of the figure that are felt sequentially while moving the figure around in the hand.

Representations of Imagery Modality

Concerning our second research question—do primary sensory cortices differentiate auditory and tactile imagery in blind and sighted participants—one possible outcome was that we would find higher classification accuracies for blind compared with sighted participants. Again, similar to the perception modality analyses, we found comparable, rather than enhanced, intra-modal representations of imagery modality between blind and sighted groups. Moreover, even though the results were not significantly different from the sighted group, we were not able to successfully classify imagery modality in primary somatosensory area 1 and 3b of the blind group. Overall, this indicates that there was no enhancement of imagery modality differentiation in the intra-modal cortices in the blind and even suggests a slight reduced representation of mental images in primary somatosensory cortex. These findings seem contrary to earlier research which showed higher brain activity in somatosensory and primary motor areas during imagined locomotion (Deutschlander et al. 2009). We should point out though that in our study, we are studying brain patterns that differentiate the 2 imagery modalities, rather than assessing the activity during tactile imagery. The results of the classification of imagery content, which are discussed in the next section, suggest that both auditory and tactile imagery (de)activate the somatosensory and motor cortex. Therefore, it might be that these representations are not very well distinguished in these parts of the cortex.

Subsequently, we investigated whether auditory and haptic imagery could be classified from brain activity in the primary visual cortex. Contrary to our expectations, we found no evidence for imagery modality discriminative patterns in the primary and secondary visual cortex of the blind participants. Sighted participants, on the other hand, did show significant classification accuracies for imagery modality in V1 and V2, even though the decoding accuracies did not differ significantly between the 2 groups. These results suggest that any imagery representations of the blind participants in primary visual cortex—if present—are not differentiated for the auditory vs. tactile domains. So far, primary visual cortex recruitment during mental imagery or working memory in early blind has only been shown during auditory perception (Lambert et al. 2004; Lewis et al. 2011), never during mental imagery in the absence of a perceptual stimulus. Also in this study, we could not find any support for cross-modal activation of primary visual cortex, which was differentiated between conditions, during mental imagery in congenitally blind. Therefore, it remains questionable whether the reorganization of primary visual cortex after visual deprivations extends to the representation of fine-grained details of imagined information. We do not, however, exclude that blind people may be able to activate primary visual cortex through imagery. A study using an imagery task in congenitally blind that compares 2 broad object categories (e.g. tactile imagery of tools vs. fruits), with a task that requires the imagery of the objects' features (e.g. detailed information on texture and shape), may be able to shed more light on this. Alternatively, as primary visual cortex plays a role in language perception in congenitally blind (Roder et al. 2002; Burton et al. 2003; Bedny et al. 2011; Lane et al. 2015), a language-based imagery task may also active primary visual cortex. In the higher visual areas, on the other hand, we could successfully classify imagery modality in blind participants in areas V3, V4, and especially in V5/MT+. Also in the sighted participants, the classification accuracies in visual cortex were highest in MT+. In MT+, the classification was perhaps more differentiated because participants were imagining rotating the 3D figure during tactile imagery, which would be motion sensitive, while this was not the case for auditory imagery.

Representations of Imagery Content

Our last research question related to the representation of imagery content. In both the blind and the sighted, we successfully predicted within-category imagery content, for example, on the basis of brain activity we could determine if a participant was thinking of voice identity 1 or 2. To our knowledge, we are the first to successfully predict within-category imagery content in the auditory domain in congenitally blind and sighted participants (see also de Borst and de Gelder 2017). We found evidence for imagined auditory content representation for angry voice identity in primary motor cortex area 4a and visual area V4 in the blind. Together with the results of the imagery modality analyses, these results provide evidence for the cross-modal activation of higher visual areas in blind participants—even in the absence of a perceptual stimulus. In the sighted participants, we found that the primary somatosensory and primary motor cortex contaioverned auditory imagery content information, but not the visual cortex. It was initially surprising to find representations of imagined voice identity in the primary motor and somatosensory cortex. However, as discussed in de Borst & de Gelder (2017), these results may suggest that participants were using an inner vocalization strategy to imagine the voices. Although participants were instructed to imagine how the voices sounded, they may have been using their "inner voice" rather than their "inner ear" for imagery. Earlier work by de Borst et al. (2016) on film professionals and nonexperts also revealed that nonexperts are more likely to use some form of inner speech as an auditory imagery strategy. Similar to the execution of vocalizations, such as speech or singing, inner speech during imagery has shown to activate the primary motor cortex and the somatosensory cortex (Ozdemir et al. 2006; Kleber et al. 2007). Also, during the imagery of non-vocal sounds, such as the melody of a tune, activation of the motor and parietal cortices has been reported (Halpern and

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Zatorre 1999). Alternatively, it could be the case that auditory imagery deactivates the primary somatosensory and motor cortex and that this deactivation is stronger for certain stimuli than others.

We did not find any evidence for enhanced representations of imagery content in the primary auditory or somatosensory cortex of blind individuals. As research has indicated that blind individuals have superior auditory and haptic perceptual capabilities, we would have expected for these abilities to be reflected in the imagery domain as well. We expected that, for example, enhanced encoding and consolidation of auditory stimuli (Stevens and Weaver 2005; Rokem and Ahissar 2009) would lead to more precise mental representations, which in turn would lead to more distinct multivariate patterns and higher classification accuracies for imagery content (de Borst et al. 2016). Instead, we found that we could not predict more imagery content in blind individuals than in sighted. Only auditory imagery of angry identity 1 versus 2 could be successfully predicted in the blind, while in the sighted participant, we could predict all other auditory imagery content.

Conclusions and Future Directions

With this study, we had a first look into intra-modal and cross-modal multivariate representations of mental imagery in the blind brain. Our results showed that after visual deprivation mental imagery follows a similar intra-modal reorganization as perception, showing comparable, rather than enhanced, intra-modal representations of imagery, and perception modality in the blind and sighted groups. Concerning the cross-modal reorganization, we found that representations of imagery and perception modality were similar in blind and sighted groups in the higher visual areas, but we found no evidence for cross-modal imagery modality information in the primary visual cortex of blind participants. Both groups did show evidence for the representation of specific-imagined auditory features in several regions of interest, including visual area V4 in the blind participants.

Although we did not find any evidence for changes in the broad intra-modal brain organization in the blind, we do not want to exclude the possibility that changes may occur at more detailed levels (as shown in a.o. Pascual-Leone and Torres 1993). For example, our whole-brain results of perception modality classification showed searchlights with classification accuracies above chance in one group, but not in the other. Although these accuracies were not statistically significant between groups, it may indicate that some differential processing occurred. On the basis of studies on neural plasticity and learning, we can presume that sustained changes in behavior, such as present in the blind, are associated with changes in cortical representations. It may be challenging, however, to show how lifelong visually-deprived experiences across a wide variety of tasks contribute to specific changes in cortical representations. One possibility would be to gather a range of demographic and behavioral data in the congenitally blind, to systematically test whether blind participants perform better at certain behavioral tasks than sighted people, and to correlate these behavioral data with brain activity or representational information. By taking a systematic approach in which separate studies each target a task that modulates specific relevant features, it would be possible to link enhanced behavior with representational changes and draw more specific conclusions about how detailed representations may be reorganized within a certain brain region. Study designs similar to perceptual expertise studies, which investigate both functional and anatomical changes (Schneider et al. 2005b), could shed more light on both intra- and cross-modal (re)organization of perception and imagery in the blind and sighted. Especially high-resolution imaging combined with multivariate analyses could contribute to unraveling local changes and provide more insight in the level of detail that is represented beyond modality or category information.

Supplementary Material

Supplementary material is available at *Cerebral Cortex* online.

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Notes

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References

Alary F, Duquette M, Goldstein R, Elaine Chapman C, Voss P, La Buissonniere-Ariza V, Lepore F. 2009. Tactile acuity in the blind: a closer look reveals superiority over the sighted in some but not all cutaneous tasks. Neuropsychologia. 47: 2037–2043.

Alary F, Goldstein R, Duquette M, Chapman CE, Voss P, Lepore F. 2008. Tactile acuity in the blind: a psychophysical study using a two-dimensional angle discrimination task. Exp Brain Res. 187:587–594.

Aleman A, van Lee L, Mantione MH, Verkoijen IG, de Haan EH. 2001. Visual imagery without visual experience: evidence from congenitally totally blind people. Neuroreport. 12: 2601–2604.

Allen EJ, Burton PC, Olman CA, Oxenham AJ. 2017. Representations of pitch and timbre variation in human auditory cortex. J Neurosci. 37:1284–1293.

Amedi A, Raz N, Azulay H, Malach R, Zohary E. 2010. Cortical activity during tactile exploration of objects in blind and sighted humans. Restor Neurol Neurosci. 28:143–156.

Amunts K, Malikovic A, Mohlberg H, Schormann T, Zilles K. 2000. Brodmann's areas 17 and 18 brought into stereotaxic space-where and how variable? Neuroimage. 11:66–84.

Anurova I, Renier LA, De Volder AG, Carlson S, Rauschecker JP. 2015. Relationship between cortical thickness and functional activation in the early blind. Cereb Cortex. 25: 2035–2048.

Bailes SM, Lambert RM. 1986. Cognitive aspects of haptic form recognition by blind and sighted subjects. Br J Psychol. 77(Pt 4): 451–458.

Bauer C, Yazzolino L, Hirsch G, Cattaneo Z, Vecchi T, Merabet LB. 2015. Neural correlates associated with superior tactile symmetry perception in the early blind. Cortex. 63:104–117.

Baumgartner E, Wiebel CB, Gegenfurtner KR. 2015. A comparison of haptic material perception in blind and sighted individuals. Vision Res. 115:238–245.

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Bedny M, Pascual-Leone A, Dodell-Feder D, Fedorenko E, Saxe R. 2011. Language processing in the occipital cortex of congenitally blind adults. Proc Natl Acad Sci U S A. 108: 4429–4434.

Benjamini Y, Hochberg Y. 1995. Controlling the false discovery rate—a practical and powerful approach to multiple testing. J Roy Stat Soc B Met. 57:289–300.

Bodegard A, Ledberg A, Geyer S, Naito E, Zilles K, Roland PE. 2000. Object shape differences reflected by somatosensory cortical activation. J Neurosci. 20:RC51.

Bonino D, Ricciardi E, Bernardi G, Sani L, Gentili C, Vecchi T, Pietrini P. 2015. Spatial imagery relies on a sensory independent, though sensory sensitive, functional organization within the parietal cortex: a fMRI study of angle discrimination in sighted and congenitally blind individuals. Neuropsychologia. 68:59–70.

Bonino D, Ricciardi E, Sani L, Gentili C, Vanello N, Guazzelli M, Vecchi T, Pietrini P. 2008. Tactile spatial working memory activates the dorsal extrastriate cortical pathway in congenitally blind individuals. Arch Ital Biol. 146:133–146.

Buchel C, Price C, Frackowiak RS, Friston K. 1998. Different activation patterns in the visual cortex of late and congenitally blind subjects. Brain J Neurol. 121(Pt 3):409–419.

Bunzeck N, Wuestenberg T, Lutz K, Heinze HJ, Jancke L. 2005. Scanning silence: mental imagery of complex sounds. Neuroimage. 26:1119–1127.

Buonomano DV, Merzenich MM. 1998. Cortical plasticity: from synapses to maps. Annu Rev Neurosci. 21:149–186.

Burton H, Diamond JB, McDermott KB. 2003. Dissociating cortical regions activated by semantic and phonological tasks: a FMRI study in blind and sighted people. J Neurophysiol. 90: 1965–1982.

Cappagli G, Gori M. 2016. Auditory spatial localization: developmental delay in children with visual impairments. Res Dev Disabil. 53–54:391–398.

Cattaneo Z, Vecchi T, Monegato M, Pece A, Cornoldi C. 2007. Effects of late visual impairment on mental representations activated by visual and tactile stimuli. Brain Res. 1148:170–176.

Cohen H, Voss P, Lepore F, Scherzer P. 2010. The nature of working memory for Braille. PLoS One. 5:e10833.

Collignon O, Dormal G, Albouy G, Vandewalle G, Voss P, Phillips C, Lepore F. 2013. Impact of blindness onset on the functional organization and the connectivity of the occipital cortex. Brain J Neurol. 136:2769–2783.

Collignon O, Vandewalle G, Voss P, Albouy G, Charbonneau G, Lassonde M, Lepore F. 2011. Functional specialization for auditory-spatial processing in the occipital cortex of congenitally blind humans. Proc Natl Acad Sci USA. 108: 4435–4440.

Cornell Karnekull S, Arshamian A, Nilsson ME, Larsson M. 2016. From perception to metacognition: auditory and olfactory functions in early blind, late blind, and sighted individuals. Front Psychol. 7:1450.

Cornoldi C, Cortesi A, Preti D. 1991. Individual differences in the capacity limitations of visuospatial short-term memory: research on sighted and totally congenitally blind people. Mem Cognit. 19:459–468.

Cornoldi C, Tinti C, Mammarella IC, Re AM, Varotto D. 2009. Memory for an imagined pathway and strategy effects in sighted and in totally congenitally blind individuals. Acta Psychol. 130:11–16.

Coullon GS, Jiang F, Fine I, Watkins KE, Bridge H. 2015. Subcortical functional reorganization due to early blindness. J Neurophysiol. 113:2889–2899.

Daselaar SM, Porat Y, Huijbers W, Pennartz CM. 2010. Modality-specific and modality-independent components of the human imagery system. Neuroimage. 52:677–685.

de Borst AW, de Gelder B. 2017. fMRI-based multivariate pattern analyses reveal imagery modality and imagery content specific representations in primary somatosensory, motor and auditory cortices. Cereb Cortex. 27:3994–4009.

de Borst AW, Sack AT, Jansma BM, Esposito F, de Martino F, Valente G, Roebroeck A, di Salle F, Goebel R, Formisano E. 2012. Integration of "what" and "where" in frontal cortex during visual imagery of scenes. Neuroimage. 60:47–58.

de Borst AW, Valente G, Jaaskelainen IP, Tikka P. 2016. Brain-based decoding of mentally imagined film clips and sounds reveals experience-based information patterns in film professionals. Neuroimage. 129:428–438.

De Volder AG, Toyama H, Kimura Y, Kiyosawa M, Nakano H, Vanlierde A, Wanet-Defalque MC, Mishina M, Oda K, Ishiwata K, et al. 2001. Auditory triggered mental imagery of shape involves visual association areas in early blind humans. Neuroimage. 14:129–139.

Deutschlander A, Stephan T, Hufner K, Wagner J, Wiesmann M, Strupp M, Brandt T, Jahn K. 2009. Imagined locomotion in the blind: an fMRI study. Neuroimage. 45:122–128.

Dietrich S, Hertrich I, Ackermann H. 2013. Ultra-fast speech comprehension in blind subjects engages primary visual cortex, fusiform gyrus, and pulvinar—a functional magnetic resonance imaging (fMRI) study. BMC Neurosci. 14: 74.

Eickhoff SB, Stephan KE, Mohlberg H, Grefkes C, Fink GR, Amunts K, Zilles K. 2005. A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. Neuroimage. 25:1325–1335.

Finocchietti S, Cappagli G, Gori M. 2015. Encoding audio motion: spatial impairment in early blind individuals. Front Psychol. 6:1357.

Focker J, Best A, Holig C, Roder B. 2012. The superiority in voice processing of the blind arises from neural plasticity at sensory processing stages. Neuropsychologia. 50:2056–2067.

Formisano E, De Martino F, Bonte M, Goebel R. 2008. "Who" is saying "what"? Brain-based decoding of human voice and speech. Science. 322:970–973.

Frost MA, Goebel R. 2012. Measuring structural-functional correspondence: spatial variability of specialised brain regions after macro-anatomical alignment. Neuroimage. 59:1369–1381.

Gaab N, Schulze K, Ozdemir E, Schlaug G. 2006. Neural correlates of absolute pitch differ between blind and sighted musicians. Neuroreport. 17:1853–1857.

Ganis G, Thompson WL, Kosslyn SM. 2004. Brain areas underlying visual mental imagery and visual perception: an fMRI study. Brain Res Cogn Brain Res. 20:226–241.

Gentaz E, Hatwell Y. 1998. The haptic oblique effect in the perception of rod orientation by blind adults. Perception Psychophys. 60:157–167.

Geyer S, Ledberg A, Schleicher A, Kinomura S, Schormann T, Burgel U, Klingberg T, Larsson J, Zilles K, Roland PE. 1996. Two different areas within the primary motor cortex of man. Nature. 382:805–807.

Geyer S, Schormann T, Mohlberg H, Zilles K. 2000. Areas 3a, 3b, and 1 of human primary somatosensory cortex. Part 2. Spatial normalization to standard anatomical space. Neuroimage. 11: 684–696.

Goebel R, Esposito F, Formisano E. 2006. Analysis of functional image analysis contest (FIAC) data with brainvoyager QX: From single-subject to cortically aligned group general

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linear model analysis and self-organizing group independent component analysis. Hum Brain Mapp. 27:392–401.

Goebel R, Hasson U, Harel M, Levy I, Malach R 2004. Statistical analyses across aligned cortical hemispheres reveal high-resolution population maps of human visual cortex.

Goebel R, Staedtler E, Munk MHJ, Muckli L 2002. Cortex-based alignment using functional and structural constraints. Neuroimage Supplement.

Goldreich D, Kanics IM. 2003. Tactile acuity is enhanced in blindness. J Neurosci. 23:3439–3445.

Good PI. 2005. Permutation, parametric and bootstrap tests of hypotheses. New York, NY: Springer Series in Statistics.

Gori M, Sandini G, Martinoli C, Burr D. 2010. Poor haptic orientation discrimination in nonsighted children may reflect disruption of cross-sensory calibration. Current Biol. 20: 223–225.

Gori M, Sandini G, Martinoli C, Burr DC. 2014. Impairment of auditory spatial localization in congenitally blind human subjects. Brain J Neurol. 137:288–293.

Gougoux F, Lepore F, Lassonde M, Voss P, Zatorre RJ, Belin P. 2004. Neuropsychology: pitch discrimination in the early blind. Nature. 430:309.

Grant AC, Thiagarajah MC, Sathian K. 2000. Tactile perception in blind Braille readers: a psychophysical study of acuity and hyperacuity using gratings and dot patterns. Percept Psychophys. 62:301–312.

Grefkes C, Geyer S, Schormann T, Roland P, Zilles K. 2001. Human somatosensory area 2: observer-independent cytoarchitectonic mapping, interindividual variability, and population map. Neuroimage. 14:617–631.

Guerreiro MJ, Putzar L, Roder B. 2016. The effect of early visual deprivation on the neural bases of auditory processing. J Neurosci. 36:1620–1630.

Halpern AR, Zatorre RJ. 1999. When that tune runs through your head: a PET investigation of auditory imagery for familiar melodies. Cereb Cortex. 9:697–704.

Halpern AR, Zatorre RJ, Bouffard M, Johnson JA. 2004. Behavioral and neural correlates of perceived and imagined musical timbre. Neuropsychologia. 42:1281–1292.

Hari R, Hamalainen M, Ilmoniemi R, Kaukoranta E, Reinikainen K, Salminen J, Alho K, Naatanen R, Sams M. 1984. Responses of the primary auditory cortex to pitch changes in a sequence of tone pips: neuromagnetic recordings in man. Neurosci Lett. 50:127–132.

Harrison SA, Tong F. 2009. Decoding reveals the contents of visual working memory in early visual areas. Nature. 458: 632–635.

He C, Peelen MV, Han Z, Lin N, Caramazza A, Bi Y. 2013. Selectivity for large nonmanipulable objects in scene-selective visual cortex does not require visual experience. Neuroimage. 79:1–9.

Heller MA. 1989a. Tactile memory in sighted and blind observers: the influence of orientation and rate of presentation. Perception. 18:121–133.

Heller MA. 1989b. Texture perception in sighted and blind observers. Percept Psychophys. 45:49–54.

Heller MA, Kappers AM, McCarthy M, Clark A, Riddle T, Fulkerson E, Wemple L, Walk AM, Basso A, Wanek C, et al. 2008. The effects of curvature on haptic judgments of extent in sighted and blind people. Perception. 37:816–840.

Herholz SC, Lappe C, Knief A, Pantev C. 2008. Neural basis of music imagery and the effect of musical expertise. Eur J Neurosci. 28:2352–2360.

Holig C, Focker J, Best A, Roder B, Buchel C. 2014a. Brain systems mediating voice identity processing in blind humans. Hum Brain Mapp. 35:4607–4619.

Holig C, Focker J, Best A, Roder B, Buchel C. 2014b. Crossmodal plasticity in the fusiform gyrus of late blind individuals during voice recognition. Neuroimage. 103:374–382.

Hubel DH, Wiesel TN. 1970. The period of susceptibility to the physiological effects of unilateral eye closure in kittens. J Physiol. 206:419–436.

Hubel DH, Wiesel TN, LeVay S. 1976. Functional architecture of area 17 in normal and monocularly deprived macaque monkeys. Cold Spring Harb Symp Quant Biol. 40:581–589.

Ishai A, Haxby JV, Ungerleider LG. 2002. Visual imagery of famous faces: effects of memory and attention revealed by fMRI. Neuroimage. 17:1729–1741.

Jafari Z, Malayeri S. 2014. Effects of congenital blindness on the subcortical representation of speech cues. Neuroscience. 258:401–409.

Jancke L, Koeneke S, Hoppe A, Rominger C, Hanggi J. 2009. The architecture of the golfer's brain. PLoS One. 4:e4785.

Jiang F, Stecker GC, Fine I. 2014. Auditory motion processing after early blindness. J Vis. 14:4.

Kattner F, Ellermeier W. 2014. Irrelevant speech does not interfere with serial recall in early blind listeners. Q J Exp Psychol. 67:2207–2217.

King AJ. 2014. What happens to your hearing if you are born blind? Brain J Neurol. 137:6–8.

Kleber B, Birbaumer N, Veit R, Trevorrow T, Lotze M. 2007. Overt and imagined singing of an Italian aria. Neuroimage. 36:889–900.

Klein I, Paradis AL, Poline JB, Kosslyn SM, Le Bihan D. 2000. Transient activity in the human calcarine cortex during visual-mental imagery: an event-related fMRI study. J Cogn Neurosci. 12(Suppl 2):15–23.

Kolarik AJ, Scarfe AC, Moore BC, Pardhan S. 2017. Blindness enhances auditory obstacle circumvention: Assessing echolocation, sensory substitution, and visual-based navigation. PLoS One. 12:e0175750.

Kosslyn SM, Alpert NM, Thompson WL, Maljkovic V, Weise SB, Chabris CF, Hamilton SE, Rauch SL, Buonanno FS. 1993. Visual mental imagery activates topographically organized visual cortex: PET investigations. J Cogn Neurosci. 5:263–287.

Kosslyn SM, Pascual-Leone A, Felician O, Camposano S, Keenan JP, Thompson WL, Ganis G, Sukel KE, Alpert NM. 1999. The role of area 17 in visual imagery: convergent evidence from PET and rTMS. Science. 284:167–170.

Kosslyn SM, Reiser BJ, Farah MJ, Fliegel SL. 1983. Generating visual images: units and relations. J Exp Psychol Gen. 112: 278–303.

Kriegeskorte N, Goebel R, Bandettini P. 2006. Information-based functional brain mapping. Proc Natl Acad Sci U S A. 103: 3863–3868.

Lambert S, Sampaio E, Mauss Y, Scheiber C. 2004. Blindness and brain plasticity: contribution of mental imagery? An fMRI study. Brain Res Cogn Brain Res. 20:1–11.

Lane C, Kanjlia S, Omaki A, Bedny M. 2015. "Visual" cortex of congenitally blind adults responds to syntactic movement. J Neurosci. 35:12859–12868.

Lerens E, Araneda R, Renier L, De Volder AG. 2014. Improved beat asynchrony detection in early blind individuals. Perception. 43:1083–1096.

Lerens E, Renier L. 2014. Does visual experience influence the spatial distribution of auditory attention? Acta Psychol (Amst). 146:58–62.

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on 29 July 2018

Lessard N, Pare M, Lepore F, Lassonde M. 1998. Early-blind human subjects localize sound sources better than sighted subjects. Nature. 395:278–280.

Lewald J. 2013. Exceptional ability of blind humans to hear sound motion: implications for the emergence of auditory space. Neuropsychologia. 51:181–186.

Lewald J, Getzmann S. 2013. Ventral and dorsal visual pathways support auditory motion processing in the blind: evidence from electrical neuroimaging. Eur J Neurosci. 38:3201–3209.

Lewis JW, Frum C, Brefczynski-Lewis JA, Talkington WJ, Walker NA, Rapuano KM, Kovach AL. 2011. Cortical network differences in the sighted versus early blind for recognition of human-produced action sounds. Hum Brain Mapp. 32: 2241–2255.

Liang M, Mouraux A, Hu L, Iannetti GD. 2013. Primary sensory cortices contain distinguishable spatial patterns of activity for each sense. Nat commun. 4:1979.

Malikovic A, Amunts K, Schleicher A, Mohlberg H, Eickhoff SB, Wilms M, Palomero-Gallagher N, Armstrong E, Zilles K. 2007. Cytoarchitectonic analysis of the human extrastriate cortex in the region of V5/MT+: a probabilistic, stereotaxic map of area hOc5. Cereb Cortex. 17:562–574.

Menard L, Cathiard MA, Troille E, Giroux M. 2015. Effects of congenital visual deprivation on the auditory perception of anticipatory labial coarticulation. Folia Phoniatr Logop. 67: 83–89.

Morosan P, Rademacher J, Schleicher A, Amunts K, Schormann T, Zilles K. 2001. Human primary auditory cortex: cytoarchitectonic subdivisions and mapping into a spatial reference system. Neuroimage. 13:684–701.

Morrongiello BA, Humphrey GK, Timney B, Choi J, Rocca PT. 1994. Tactual object exploration and recognition in blind and sighted children. Perception. 23:833–848.

Murphy MC, Nau AC, Fisher C, Kim SG, Schuman JS, Chan KC. 2016. Top-down influence on the visual cortex of the blind during sensory substitution. NeuroImage. 125:932–940.

Nilsson ME, Schenkman BN. 2016. Blind people are more sensitive than sighted people to binaural sound-location cues, particularly inter-aural level differences. Hearing Res. 332: 223–232.

Noordzij ML, Zuidhoek S, Postma A. 2007. The influence of visual experience on visual and spatial imagery. Perception. 36:101–112.

Norman JF, Bartholomew AN. 2011. Blindness enhances tactile acuity and haptic 3-D shape discrimination. Atten Percept Psychophys. 73:2323–2331.

Occelli V, Lin JB, Lacey S, Sathian K. 2014. Loss of form vision impairs spatial imagery. Front Hum Neurosci. 8:159.

Occelli V, Spence C, Zampini M. 2013. Auditory, tactile, and audiotactile information processing following visual deprivation. Psychol Bull. 139:189–212.

Ozdemir E, Norton A, Schlaug G. 2006. Shared and distinct neural correlates of singing and speaking. Neuroimage. 33: 628–635.

Park HJ, Chun JW, Park B, Park H, Kim JI, Lee JD, Kim JJ. 2011. Activation of the occipital cortex and deactivation of the default mode network during working memory in the early blind. J Int Neuropsychol Soc. 17:407–422.

Pascual-Leone A, Torres F. 1993. Plasticity of the sensorimotor cortex representation of the reading finger in Braille readers. Brain. 116(Pt 1):39–52.

Pasqualotto A, Newell FN. 2007. The role of visual experience on the representation and updating of novel haptic scenes. Brain Cogn. 65:184–194.

Picard D, Lebaz S, Jouffrais C, Monnier C. 2010. Haptic recognition of two-dimensional raised-line patterns by early-blind, late-blind, and blindfolded sighted adults. Perception. 39: 224–235.

Plailly J, Delon-Martin C, Royet JP. 2012. Experience induces functional reorganization in brain regions involved in odor imagery in perfumers. Hum Brain Mapp. 33:224–234.

Postma A, Zuidhoek S, Noordzij ML, Kappers AM. 2007. Differences between early-blind, late-blind, and blindfolded-sighted people in haptic spatial-configuration learning and resulting memory traces. Perception. 36:1253–1265.

Postma A, Zuidhoek S, Noordzij ML, Kappers AM. 2008. Haptic orientation perception benefits from visual experience: evidence from early-blind, late-blind, and sighted people. Percept Psychophys. 70:1197–1206.

Recanzone GH, Schreiner CE, Merzenich MM. 1993. Plasticity in the frequency representation of primary auditory cortex following discrimination training in adult owl monkeys. J Neurosci. 13:87–103.

Reed CL. 2002. Tactile Perception. In: Ramachandran VS, editor. Encyclopedia of the Human Brain. 4th ed. San Diego (CA): Academic Press.

Reed CL, Shoham S, Halgren E. 2004. Neural substrates of tactile object recognition: an fMRI study. Hum Brain Mapp. 21: 236–246.

Ricciardi E, Vanello N, Sani L, Gentili C, Scilingo EP, Landini L, Guazzelli M, Bicchi A, Haxby JV, Pietrini P. 2007. The effect of visual experience on the development of functional architecture in hMT+. Cereb Cortex. 17:2933–2939.

Roder B, Rosler F, Hennighausen E. 1997. Different cortical activation patterns in blind and sighted humans during encoding and transformation of haptic images. Psychophysiology. 34:292–307.

Roder B, Rosler F, Neville HJ. 2001. Auditory memory in congenitally blind adults: a behavioral-electrophysiological investigation. Brain Res Cogn Brain Res. 11:289–303.

Roder B, Stock O, Bien S, Neville H, Rosler F. 2002. Speech processing activates visual cortex in congenitally blind humans. Eur J Neurosci. 16:930–936.

Rokem A, Ahissar M. 2009. Interactions of cognitive and auditory abilities in congenitally blind individuals. Neuropsychologia. 47:843–848.

Rosler F, Roder B, Heil M, Hennighausen E. 1993. Topographic differences of slow event-related brain potentials in blind and sighted adult human subjects during haptic mental rotation. Brain Res Cogn Brain Res. 1:145–159.

Sathian K, Lacey S. 2007. Journeying beyond classical somatosensory cortex. Can J Exp Psychol. 61:254–264.

Schepers IM, Hipp JF, Schneider TR, Roder B, Engel AK. 2012. Functionally specific oscillatory activity correlates between visual and auditory cortex in the blind. Brain J Neurol. 135: 922–934.

Schmidt TT, Ostwald D, Blankenburg F. 2014. Imaging tactile imagery: changes in brain connectivity support perceptual grounding of mental images in primary sensory cortices. Neuroimage. 98:216–224.

Schneider P, Sluming V, Roberts N, Bleeck S, Rupp A. 2005a. Structural, functional, and perceptual differences in Heschl's gyrus and musical instrument preference. Ann N Y Acad Sci. 1060:387–394.

Schneider P, Sluming V, Roberts N, Scherg M, Goebel R, Specht HJ, Dosch HG, Bleeck S, Stippich C, Rupp A. 2005b. Structural and functional asymmetry of lateral Heschl's gyrus reflects pitch perception preference. Nat Neurosci. 8:1241–1247.

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on 29 July 2018

Simoes-Franklin C, Whitaker TA, Newell FN. 2011. Active and passive touch differentially activate somatosensory cortex in texture perception. Hum Brain Mapp. 32:1067–1080.

Stevens AA, Weaver K. 2005. Auditory perceptual consolidation in early-onset blindness. Neuropsychologia. 43:1901–1910.

Striem-Amit E, Amedi A. 2014. Visual cortex extrastriate body-selective area activation in congenitally blind people "seeing" by using sounds. Curr Biol. 24:687–692.

Striem-Amit E, Cohen L, Dehaene S, Amedi A. 2012a. Reading with sounds: sensory substitution selectively activates the visual word form area in the blind. Neuron. 76:640–652.

Striem-Amit E, Dakwar O, Reich L, Amedi A. 2012b. The large-scale organization of "visual" streams emerges without visual experience. Cereb Cortex. 22:1698–1709.

Strnad L, Peelen MV, Bedny M, Caramazza A. 2013. Multivoxel pattern analysis reveals auditory motion information in MT+ of both congenitally blind and sighted individuals. PLoS One. 8:e63198.

Sunanto J, Nakata H. 1998. Indirect tactual discrimination of heights by blind and blindfolded sighted subjects. Percept Mot Skills. 86:383–386.

Talairach J, Tournoux P. 1988. Co-planar stereotaxic atlas of the human brain: 3-dimensional proportional system: an approach to cerebral imaging. Stuttgart; New York: Georg Thieme.

Tao Q, Chan CC, Luo YJ, Li JJ, Ting KH, Wang J, Lee TM. 2015. How does experience modulate auditory spatial processing in individuals with blindness? Brain Topogr. 28:506–519.

Tartaglia EM, Bamert L, Mast FW, Herzog MH. 2009. Human perceptual learning by mental imagery. Curr Biol. 19:2081–2085.

Van Boven RW, Hamilton RH, Kauffman T, Keenan JP, Pascual-Leone A. 2000. Tactile spatial resolution in blind braille readers. Neurology. 54:2230–2236.

van den Hurk J, Van Baelen M, Op de Beeck HP. 2017. Development of visual category selectivity in ventral visual cortex does not require visual experience. Proc Natl Acad Sci USA. 114:E4501–E4510.

Vanlierde A, De Volder AG, Wanet-Defalque MC, Veraart C. 2003. Occipito-parietal cortex activation during visuo-spatial imagery in early blind humans. Neuroimage. 19:698–709.

Vanlierde A, Wanet-Defalque MC. 2004. Abilities and strategies of blind and sighted subjects in visuo-spatial imagery. Acta Psychol (Amst). 116:205–222.

Vetter P, Smith FW, Muckli L. 2014. Decoding sound and imagery content in early visual cortex. Curr Biol. 24:1256–1262.

Voss P. 2016. Auditory spatial perception without vision. Front Psychol. 7:1960.

Voss P, Lassonde M, Gougoux F, Fortin M, Guillemot JP, Lepore F. 2004. Early- and late-onset blind individuals show supra-normal auditory abilities in far-space. Curr Biol. 14:1734–1738.

Voss P, Tabry V, Zatorre RJ. 2015. Trade-off in the sound localization abilities of early blind individuals between the horizontal and vertical planes. J Neurosci. 35:6051–6056.

Voss P, Zatorre RJ. 2012. Occipital cortical thickness predicts performance on pitch and musical tasks in blind individuals. Cereb Cortex. 22:2455–2465.

Wanet-Defalque MC, Veraart C, De Volder A, Metz R, Michel C, Dooms G, Goffinet A. 1988. High metabolic activity in the visual cortex of early blind human subjects. Brain Res. 446:369–373.

Watkins KE, Cowey A, Alexander I, Filippini N, Kennedy JM, Smith SM, Ragge N, Bridge H. 2012. Language networks in anophthalmia: maintained hierarchy of processing in 'visual' cortex. Brain J Neurol. 135:1566–1577.

Watkins KE, Shakespeare TJ, O'Donoghue MC, Alexander I, Ragge N, Cowey A, Bridge H. 2013. Early auditory processing in area V5/MT+ of the congenitally blind brain. J Neurosci. 33:18242–18246.

Wilms M, Eickhoff SB, Specht K, Amunts K, Shah NJ, Malikovic A, Fink GR. 2005. Human V5/MT+: comparison of functional and cytoarchitectonic data. Anatomy Embryol. 210:485–495.

Zvyagintsev M, Clemens B, Chechko N, Mathiak KA, Sack AT, Mathiak K. 2013. Brain networks underlying mental imagery of auditory and visual information. Eur J Neurosci. 37: 1421–1434.

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