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Functional Changes in People with Different Hearing Status and Experiences of using Chinese Sign Language: An fMRI study

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ABSTRACT

The purpose of this study was to assess functional changes in the cerebral cortex in people with different sign language experience and hearing status whilst observing and imitating Chinese Sign Language (CSL) using functional Magnetic Resonance Imaging (fMRI). 50 participants took part in the study, and were divided into four groups according to their hearing status and experience of using sign language:

prelingual deafness signer group (PDS), normal hearing non-signer group (HnS), native signer group with normal hearing (HNS), and acquired signer group with normal hearing (HLS). fMRI images were scanned from all subjects when they performed block-designed tasks that involved observing and imitating sign language stimuli. Nine activation areas were found in response to undertaking either observation or imitation CSL tasks and three activated areas were found only when undertaking the imitation task. Of those, the PDS group had significantly greater activation areas in terms of the cluster size of the activated voxels in the bilateral superior parietal lobule, cuneate lobe and lingual gyrus in response to undertaking either the observation or the imitation CSL task than the HnS, HNS and HLS groups. The PDS group also showed significantly greater activation in the bilateral inferior frontal gyrus which was also found in the HNS or the HLS groups but not in the HnS group. This indicates that deaf signers have better sign language proficiency, because they engage more actively with the phonetic and semantic elements. In addition, the activations of the bilateral superior temporal gyrus and inferior parietal lobule were only found in the PDS group and HNS group, and not in the other two groups, which indicates that the area for sign language processing appears to be sensitive to the age of language acquisition.

Key Words: fMRI; hearing status; Chinese sign language experience; deaf signers, sign language acquisition.

1. INTRODUCTION

Normal hearing is crucial for speech and language development in early childhood. When moderate or severe hearing impairment occurs in children between the ages of 0 to 5 years, speech or language development is most likely to be delayed. An individual born with hearing impairment or who had a hearing deficit, prior to the age at which speech is acquired, is referred to as prelingual deafness (Gleason & Ratner, 2009; Martines, Martines, Mucia, Sciacca, & Salvago, 2013). In contrast, if the severe hearing impairment occurs after the acquisition of speech and language either due to sudden hearing loss or a gradual progression, it is referred to as postlingual deafness (Okazawa, Naito, & Yonekura, 1996; Ahmad et al., 2012). The communication difficulty of using oral language is one of the most common problems encountered by people with either prelingual or postlingual deafness (Gregory & Hindley,1996; Uylings, 2006). For them, sign language is often used as an alternative form of communication in order to overcome such challenges (Corina & McBurney, 2001; MacSweeney, Woll, & Campbell, 2002; Uylings, 2006; Wasserman, 2007).

Language is a special function of the human brain and offers an indispensable tool for communication. Language acquisition is one of the most fundamental human traits, and various studies have shown an important correlation between brain development and language acquisition in children with normal hearing (Casey, Giedd, & Thomas, 2000; Kuhl & Rivera-Gaxiola, 2008; Sadato, Yamada, & Okada, 2004, Sakai, Tatsuno, Suzuki, Kimura, & Ichida, 2005, Saffran, Werker, & Werner, 2006; Uylings, 2006). For example, in early childhood language acquisition, the brain stores linguistic information and adapts to the grammatical regularities of language. By the time a child is three years old, 97% of children are able to connect 2–3 words to form phrases and simple sentences (Uylings, 2006; Wasserman, 2007).

Recent advances in neuro-functional imaging techniques provide evidence for visualizing the brain activation regions responsible for language processing and production (e.g., Price, 2010). Several important structures of the brain have been extensively researched in order to explore the neural bases of language acquisition. Evidence shows that the inferior frontal lobe (specifically Broca's area) and the posterior superior temporal gyrus (Wernicke's area) play an important role in speech perception and language acquisition (Price, 2000; Hickok and Poeppel, 2004; Caplan, 2000; Petitto et al., 2000).

Furthermore, apart from the Wernicke's and Broca's areas, various recent studies have shown that there are many other areas in the left and right hemispheres that are activated when different language tasks are undertaken (Ocklenburg, Hugdahl, & Westerhausen, 2013; Zacà, Jarso, & Pillai, 2013). For example, several fMRI studies found activation in the left middle frontal gyrus and anterior cingulate gyrus as well as in the superior parietal lobe during sentence completion and verb production (Kircher et al., 2009; Shapiro et al., 2001; Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004) and is suggested to be involved in retrieval of associations during semantic processing (Carreiras et al., 2009). In addition to the left-hemispheric activation described above, various studies have shown the contribution of the right hemisphere, which is mainly involved in the process of integrating language tasks or as an additional resource in tasks of increased difficulty, such as sentence completion, decoding ambiguity, metaphors and distant semantic relationships. Moreover, activation in right-hemispheric areas is increased when higher cognitive demands are needed (Dräger et al., 2004).

Sign language is an accepted language, which uses visually transmitted sign patterns (manual communication, body language) to convey meaning, simultaneously using hand shapes, orientation and movement of the hands arms or body, and facial expressions to express a speaker's thoughts. Although the complex spatial arrangement and grammar structure of sign language is markedly different from spoken languages, multiple studies have confirmed that sign languages, just as spoken languages, make special use of left-lateralized language networks (e.g., Broca's and Wernicke's areas), which are activated in people with normal hearing, i.e., Broca's area is associated with sign language production just as it is in speech production in people with normal hearing (Rauschecker & Tian, 2000), and Wernicke's area is related to the perception of meaningful sign language (Neville, Bavelier, & Corina,1998; Nishimura, Hashikawa, & Doi,1999; Petitto et al., 2000; Soderfeldt, Ronnberg, & Risberg,1994; Campbell, MacSweeney, & Waters, 2008).

Recent neuroimaging studies have also shown that early acquisition of sign language has an effect on a broad network of brain regions, leading to more right hemisphere involvement in sign language processing (Neville et al. 1997, 1998; Newman et al. 2002). Evidence obtained from studies using fMRI have demonstrated that the specific requirements for sign language processing also shape functional organization of language systems in the brain, and most of the functional areas responsible for language are shared by prelingually deaf people and people with normal hearing, even though deaf people have abnormal peripheral auditory systems (Hardie & Shepherd,1999; MacSweeney et al., 2002; Weisberg, Koo, Crain, & Eden, 2012). Therefore, functional adaptations of the human brain for language acquisition occur when there is an early language exposure to complex linguistic stimuli, using either auditory or visual stimuli.

Although neuroimaging and behavioural studies indicate that the modality of the native language does lead to some differences in specialization of brain regions, they also demonstrate that the availability of complex linguistic input in either visual or auditory modality early in life is correlated with engagement of specialized neural networks for linguistic tasks, together with linguistic proficiency. It is still unclear what effect neural changes engendered by the exposure to both auditory and visual modality at different stage of life have on first and second language acquisition. The purpose of this study was to investigate functional changes in the cerebral cortex when observing and imitating Chinese Sign Language (CSL) in people with different CSL experience and hearing status using fMRI.

MATERIALS AND METHODS

2.1 Participants

A total of 50 right-handed participants were invited to take part in the study. They were divided into four groups based on the study design which considered their hearing status and experience of using sign language, and the detailed information is shown in Table 1, i.e.

Group 1- Prelingual deafness signer group (PDS): All subjects in the PDS group had severe or profound sensorineural hearing loss before 2 years of age. 12 PDS reported they had become deaf as a result of - drug toxicity, whereas two others were congenitally deaf from birth.

Group 2- Normal hearing but not signer control group (HnS): The subjects in the HnS group had never learned - Chinese Sign Language (CSL).

Group 3- Native signer with normal hearing group (HNS): The subjects in the HNS were born to deaf parents and acquired both CSL and Chinese as native languages from birth.

Group 4- Late (Acquired) signer group with normal hearing (HLS): All of them were trained as sign language interpreters with acquired CSL after the age of 18. They could master commonly used sign language after 2-4 years (mean duration=2.5 years).

2.2 Experiment design and materials

Eight pictures with Chinese sign language presented by a male deaf signer showing meaningful words were used in the present study. These simple words were commonly used in daily life. They were,

'Hello' (您好); 'Thank you' (谢谢); 'I am happy' (我很高兴); 'You are great' (你很不错);'I love you' (我爱你), 'It is a nice day' (天气很好); 'Nice to meet you' (见到你很高兴) and 'I am fine' (我很好).

Of these, four pictures were chosen at random for the experiment. According to the study design, all participants were asked to observe and imitate the CSL shown in the pictures. For those who had previous CSL experience (i.e., PDS, HNS and HLS groups), these tasks were relatively easy. However, the participants who had no previous experience of CSL (i.e., HnS group) were encouraged to observe the pictures carefully and imitate the signs as closely as they could, regardless of whether they understood their meaning.

Figure 1 shows the experimental block design, consisting of an intermittent stimulus mode with 7 rest and 6 task periods (20 seconds each in duration). Within the task periods, there were three observation and three imitation sessions of CSL. During each 20-second task period, as indicated above, four different pictures with CSL were presented, and each lasted for approximately 5 seconds for either observation or imitation. The same CSL pictures were used in each task period. During the 20-second rest period, the participants rested their eyes on a black "+" on the computer screen. All participants were asked the recognition questions at the end of each run to ensure that their attention was focused on the stimuli.

INSERT FIGURE 1 NEAR HERE

fMRI and Imaging Parameters

All of the examinations were carried out using a 1.5T Marconi Eclipse System (USA). The participants were requested to lie on their back with their head fixed in the standard quadrature head coil with head strap and support pads to secure the head position.

The functional images were obtained using spin echo (SE), echo planar (EPI) sequences with the following parameters:

The parameters for a transversal SE T1WI sequence: TR/TE 500 ms/12 ms，FOV 240 mm×240 mm， flip angle 90°; matrix size =192×256; slice thickness 6.0 mm without intervals. There were 20 continuous slices. Total scanning time was approximately 3 minutes and 12 seconds;

The parameters for a transversal EPI sequence: TR/TE 3000 ms/40 ms，FOV 240 mm x 240 mm，the in-plane matrix=128 x 128. Twenty slices parallel to the anterior-posterior commissural (AC-PC) line were scanned with thickness of 6.0 mm and the number of dynamics was 130 runs.

3D images used for anatomical reference were scanned using a RF-FAST sequence with the following parameters: TR = 12 ms, TE = 4.47 ms, FOV = 240mm x 240mm, the flip angle was 20 degree, the matrix size was 192 x 256 pixels. There were 182 continuous slices with 1.0 mm thickness. Total scanning time was approximately eight and a half minutes.

2.4 Imaging Data Analysis

All image data pre-processing and analysis was performed using AFNI software (Cox, 1996). A cluster of the activated voxels was determined using a general linear model (GLM) on the basis of Statistical Parametric Mapping (SPM). For each participant, post-processing data included motion correction, spatial standardization and space smoothing to obtain the average activation map. The size of space smoothing kernel was 8. High-resolution 3D T1-weighted images served as a matrix for the spatial standardization. The standardized Talairach stereotaxic space template was used to orient the brain areas. The hemodynamic response was modelled with the canonical HRF, and it was convolved with the stimuli as the standard procedure. Only where the hemodynamic curve obtained from an individual voxel correlated well with the standard function curve was it considered as an activated area. In addition, a cluster size of the activated voxels larger than 100 mm^3 and radius greater than 5 mm was defined as a region of interests (ROIs). A *p* value less than 0.05 was considered as significant and the cluster determination was performed on the first (subject) level.

INSERT FIGURE 2 NEAR HERE

2.5 Data management and statistical analyses

As part of the routine data acquisition and analysis, both spatial extent (cluster size) and strength (intensity change) were measured and analysed in the present study. However, due to there being no significant statistical differences in the intensity changes among the groups, together with the complexity of the results, the results of the intensity changes were not presented in the manuscript.

For the statistical analysis, 'Analysis of covariance (ANCOVA) test' was chosen for group comparisons as the basis for considering the potential effects of other co-variables (i.e., age and gender factors). The ANCOVA can be viewed as a specialized GLM combining multiple regression and analysis of variance, which increases statistical power between groups and reduces the unexplained variance error within-group.

In the present study, the ANCOVA test was performed to examine the effects of sign language experience and hearing status (PDS, HnS, HNS, and HLS groups), together with age and gender as nuisance covariates on the cluster size of the activated voxels. The mean value and standard deviation of clusters of the activated voxels were calculated and compared using a post-hoc test (i.e., Tukey HSD) when significant differences in the cluster size were found between the groups using the ANCOVA. A paired t-test was performed when comparing the cluster sizes of the activated voxels in the conditions of observing and imitating CSL. Statistical analyses were performed using the software SPSS (version 19.0, SPSS Inc., Chicago, USA). A $p<0.05$ was considered to be statistically significant.

2.6 Ethical Consideration

Ethical approval was obtained from the Institutional Review Board (IRB) of Tianjin First Central Hospital and the Research Ethics Committee of Tianjin University of Technology. The participants took part in the study on a voluntary basis and no financial compensation was offered. Written consent was obtained from all participants before proceeding with any of the study procedures.

3. RESULTS

Table 1 shows demographic data, together with hearing status and experience of using sign language in the four groups. No statistical differences were found in either age or gender among four groups (ANCOVA and Chi-square test for the age and gender respectively, $p>0.05$).

INSERT TABLE 1 NEAR HERE

Based on the criteria of significant clusters of the activated voxels described in Section 2.4, Figure 3 summarizes all activation areas found whilst undertaking either observation or imitation CSL tasks. Nine activation areas were found in response to undertaking either observation or imitation CSL tasks (i.e., bilateral middle frontal gyrus, middle temporal gyrus, superior parietal lobule, superior parietal lobule, cuneate lobe, fusiform gyrus, lingual gyrus, superior temporal gyrus, and inferior frontal gyrus) (Figure 3, left and middle panels), and three activated areas were found only when undertaking the imitation task. They were precentral gyrus, paracentral lobule and cerebellar hemisphere (Figure 3, right panel). By using paired *t*-test, there were no significant differences in the cluster sizes of the activated voxels between left and right sides in all groups whilst undertaking the task (paired *t*-test, $p>0.05$).

INSERT FIGURE 3 NEAR HERE

Moreover, several activation areas without significant differences in terms of the cluster size of the activated voxels were found in all groups, including bilateral middle frontal gyrus, middle temporal gyrus and fusiform gyrus (Figure 3, left panel). By contrast, the cluster size of the activated voxels in the bilateral superior parietal lobule, cuneate lobe and lingual gyrus differed significantly in all groups (Figure 3, middle panel). Further analysis showed that the PDS group had significantly greater cluster size of the activated voxels in these areas in response to undertaking either the observation or the imitation CSL task than the HnS, HNS and HLS groups. The HNS group also demonstrated significantly greater cluster size of the activated voxels in the left superior parietal lobule than the HLS group whilst undertaking the observing CSL task ($p<0.05$) (Tables 2). In addition, the cluster size of the activated voxels in the left cuneate lobule obtained from the HnS group were greater than those in the HNS and HLS groups whilst undertaking the imitating CSL task ($p<0.05$) (Table 4).

Furthermore, activations of the bilateral inferior frontal gyrus were found in the PDS, HNS and HLS groups, but no activation in the HNS group. The PDS group showed significantly greater cluster size of the activated voxels in the bilateral inferior frontal gyrus in response to undertaking either the observation or imitation CSL task than either the HNS or the HLS groups. In addition, the activations of bilateral superior temporal gyrus and inferior parietal lobule were only found in the PDS group and HNS group, but not in the other two groups. Further analysis showed that the cluster size of the activated voxels in the superior temporal gyrus in the PDS group were greater than those in the HNS group. However, there was no significant difference in inferior parietal lobule between the PDS group and HNS group (Tables 2 and 4).

INSERT TABLE 2 NEAR HERE

INSERT TABLE 3 NEAR HERE

Figure 4 shows a comparison of the cluster sizes of the activated voxels obtained from four individuals in different groups while undertaking the observation CSL task. The cluster sizes of the activated voxels in the bilateral inferior frontal gyrus in the PDS group (left top, Red arrows) were greater than those in the HNS group (left bottom) and HLS (right bottom), the cluster sizes of the activated voxels in the bilateral superior temporal gyrus in the PDS group were greater than those in the HNS group

(Pink arrows), and the cluster sizes of the activated voxels in the bilateral superior parietal lobule, cuneate lobe and lingual gyrus in the PDS group was greater than those in other groups (Blue and Light pink arrows).

INSERT FIGURE 4 NEAR HERE

A series of paired *t*-tests was used to compare the cluster sizes of the activated voxels between the observing CSL and imitating CSL tasks in four different groups. In the PDS group, the cluster sizes of the activated voxels in the bilateral inferior frontal gyrus, superior parietal lobule and left middle temporal gyrus when imitating CSL were significantly greater than those when observing CSL (left and right inferior frontal gyrus: $t(l)$=-13.39, $t(r)$=-19.14, p<0.0005; left superior parietal lobule: $t(l)$=-14.10, $t(r)$=-14.86, p<0.0005; left middle temporal gyrus: $t(l)$=-2.72, p<0.05). Figure 5 shows an example of comparisons in these areas whilst observing CSL (left panel) and imitating CSL (right panel) in a prelingual deafness signer.

INSERT FIGURE 5 NEAR HERE

Furthermore, in the HNS and HLS groups, the cluster sizes of the activated voxels in the bilateral inferior frontal gyrus when imitating CSL were also significantly greater than those observing CSL (HNS: $t(l)$=-9.38; $t(r)$=- 9.53; p<0.0005; HLS: $t(l)$=-4.18, p<0.005; borderline significance in right inferior frontal gyrus, t=-2.17, p=0.062). However, there were no significant differences in any cluster sizes of the activated voxels between the observing CSL and imitating CSL tasks in the HnS group (p>0.05).

4. DISCUSSION

fMRI has been widely used in previous studies to investigate sign language and brain development, particularly on brain lateralisation and early acquisition using visual/spatial modality (MacSweeney et al., 2002; Neville et al., 1998; Nishimura et al.,1999; Weisberg et al., 2012). Various early and recent studies on the neurolinguistics of sign languages have confirmed that sign languages, just as spoken languages, make special use of left-lateralized language networks (Campbell et al., 2008), although early acquisition of sign language has been found to lead to more right hemisphere involvement in sign language processing (Neville et al. 1997, 1998; Newman et al. 2002; Damasio, 2005). For example, a study of American Sign Language (ASL) by Neville et al. (1998), compared activated areas among deaf people and native signers with normal hearing using fMRI, and apart from the important roles played by the Broca's area and the Wernicke's area in the left hemisphere for speech perception and language acquisition, results revealed that the right hemisphere (superior temporal gyrus and angular gyrus), known for specialized visuospatial information, was engaged to a greater extent in both deaf people and hearing native signers using ASL than in hearing non-signers reading English.

Furthermore, current neuroimaging data suggest that activations of the areas for sign language processing appear to be sensitive to the age of language acquisition. In the studies by Neille et al. (1997, 1998), they investigated the organization of neural systems in deaf and hearing native signers and in hearing subjects who acquired ASL late or not at all, when they viewed ASL signs that formed sentences. The results indicated that the effects of early acquisition of ASL include an increased role for the right hemisphere and for the parietal cortex and this occurs in both hearing and deaf native signers. Similar results were obtained from the present study. Activation of the bilateral inferior parietal lobe and superior temporal gyrus was only found in deaf and native hearing signers, not in acquired ASL signers. As the inferior parietal lobe has been particularly implicated in the processing of space-related information (Amorapanth, Widick & Chatterjee 2009; Emmorey et al., 2005), the studies by Emmorey and colleagues (2005, 2009) confirmed that extensive experience of the native signers enhanced the parietal cortex activation for processing linguistic representations of spatial relations, unlike non-signing English speakers, who mostly engaged less activities in the parietal cortex (Damasio, Grabowski, , Tranel, , Ponto, , Hichwa, , & Damasio, 2001).

In the present study, native deaf signers (i.e., PDS group) demonstrated significantly greater activation in some areas in response to CSL than native and acquired CSL signers (i.e., HNS and HLS groups), such as, the cluster size of the activated voxels in the left superior temporal gyrus in the PDS group was significantly greater than that of the HNS group when observing CSL. These results are consistent with previous studies (e.g., Petitto et al., 2000; MacSweeney et al., 2002), when they investigated cerebral activity in native signers while processing BSL and audio-visual English. The function of the inferior frontal gyrus (e.g., BA 44/45) has been recognized in association with language perception and production, independent of stimulus modality (signing or speaking) (Corina, San Jose-Robertson, Guillemin, High, & Braun, 2003; MacSweeney et al. 2004, 2008; Neville et al. 1997, 1998; Petitto et al. 2000; San Jose-Robertson, Corina, Ackerman, Guillemin, & Braun, 2004), while the left superior temporal gyrus (i.e., Wernicke's area) mainly carries out processing of spoken language in response to auditory stimuli. Due to the lack of auditory stimuli, these areas, not specialized for auditory processing in deaf signers, are engaged for other forms of linguistic processing of sign language, and consequently some cortex tissue becomes responsible for processing visual stimuli in deaf signers. Therefore, areas of the inferior frontal gyrus and the superior temporal gyrus are most likely to be associated with cross-model reorganization. In addition, the current results also suggest that deaf signers have better sign language proficiency, and thus they sign more actively with the phonetic and semantic elements because CSL is their only tool for language communication. Moreover, it is noteworthy that in the present study, no activation of the bilateral inferior frontal gyrus was found in the HnS group. This result could be interpreted as CSL experience affects activation in this area, but not meaningless CSL stimuli and hand moving.

Several common clusters of the activated voxels were found in all groups (such as bilateral middle frontal gyrus, middle temporal gyrus, and fusiform gyrus), but no significant differences were detected when conducting either an observing or an imitating task. This result indicates that these areas have a role to play in the process of observing and imitating CSL, but they are not associated with CSL experience and hearing status. It is likely that this is due to the cortical functions involved in processing and integrating spatial element analysis and visual perception (Onitsuka et al., 2004).

By comparing the areas activated in observing and imitating CSL, the results obtained from the present study show that the cluster size of the activated voxels in the inferior frontal gyrus was greater during imitating CSL than they were during observing CSL in PDS, HNS and HLS groups, indicating that more activities were involved in producing CSL during the imitating task. Moreover, the PDS group also had significantly greater activation areas in the middle temporal gyrus and superior parietal lobule whilst undertaking the imitating task. This may reflect the proficiency of CSL in deaf signers, which increases the degree of activation areas involved in the processing of sign language.

It is noteworthy that, in the present study, the bilateral precentral gyrus, paracentral lobule and cerebellar hemisphere were activated while imitating CSL, but were not activated while observing CSL. This result suggests these areas are related to hand movements, regulation and coordination of movement, and posture while imitating CSL rather than linguistic semantics of the CSL.

5. CONCLUSION

Many areas of activation were found in the groups with different sign language experience and hearing status in response to undertaking either the observing or the imitating CSL tasks. The activation of the bilateral inferior parietal lobe and superior temporal gyrus found only in deaf and hearing native signers, indicates that the areas for sign language processing appear to be sensitive to the age of language acquisition. Deaf signers demonstrated significantly greater areas of activation in response to CSL than hearing signers and people without any CSL experience. Furthermore, there were increased areas of activation involved in producing CSL during the imitating task, particularly in experienced signers.

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8. Captions of Figures

Figure 1 Diagram of the experimental block design consisting of an intermittent stimulus mode with rest and task periods

Figure legend:

There were three observation and three imitation sessions of CSL. During each 20-second task period, four different pictures with CSL (i.e., A, B, C and D) were presented, and each lasted for approximately 5 seconds for either observation or imitation. There were seven intermittent rest periods of 20 seconds' duration between tasks

Figure 2 Summary of activated areas whilst undertaking CSL observation and imitation tasks in the four groups

Figure 3 Comparison of activated areas obtained from four individuals in the different groups whilst undertaking CSL observation tasks.

Figure legend:

Red arrow: activated area of the inferior frontal lobe;

Pink arrow: activated area of the temporal superior gyrus;

Green arrow: activated area of the inferior parietal lobe;

Blue arrow: the cuneate lobe;

Light pink arrow: activated area of the superior parietal lobe.

Figure 4 An example of a comparison of the areas with significant differences whilst undertaking CSL observation and imitation tasks in a prelingual deafness signer.

Figure legend:

Red arrow: activated area of the inferior frontal lobe;

Pink arrow: activated area of the middle temporal gyrus;

Blue arrow: activated area of the superior parietal lobe.

Table1. The demographic data together with hearing status and nature of using sign language for the four different groups.

	Number	M:F	Averaged Age	Hearing Status	Nature of using sign language
PDS *group*	14	4:10	21.9	Profound deaf	Deaf native CSL user
HnS *group*	13	5:8	23.2	Normal hearing	No experience of using CSL
HNS *group*	11	8:3	22.9	Normal hearing	Hearing native CSL user
HLS *group*	12	5:7	22.5	Normal hearing	Acquired CSL user (after 18 years old)

Table 2. The cluster szie of the activated voxels (mm^3) in four groups whilst observing CSL (Mean±SD)

Active Area	DS Group	HnS Group	HNS Group	HLS Group	*F*	*p*
L middle frontal gyrus	81.27±18.78	91.73±28.79	72.78±17.96	72.22±18.76	1.773	0.170
R middle frontal gyrus	98.00±23.44	87.73±22.81	83.78±14.18	83.89±12.21	1.233	0.312
L inferior frontal gyrus	94.73±19.27	—	75.22± 8.06*	68.22±10.20*	9.840	0.001
R inferior frontal gyrus	89.82± 9.72	—	76.56± 8.97*	69.22± 8.61*	13.092	0.000
L superior temporal gyrus	31.82±33.38	—	25.67±13.58*	—	79.571	0.000
R superior temporal gyrus	40.55±56.10	—	24.67± 7.05*	—	37.542	0.000
L middle temporal gyrus	78.18±18.25	77.09±12.94	71.44±13.31	76.67±16.63	0.356	0.785
R middle temporal gyrus	75.45±16.34	78.18±12.24	82.00±14.92	75.00±13.21	0.473	0.703
L inferior parietal lobule	85.73±16.03	—	81.89± 9.85	—	0.392	0.539
R inferior parietal lobule	83.55±23.61	—	80.89±13.81	—	0.089	0.769
L superior parietal lobule	95.45±11.78	71.36± 9.09*	80.11±14.20*	65.44±10.77*#	13.318	0.000
R superior parietal lobule	06.82±11.97	72.82± 8.29*	73.33± 9.96*	70.56± 9.30*	31.785	0.000
L cuneate lobe	10.82±12.75	85.45±13.37*	77.11±10.81*	77.56± 7.75*	19.447	0.000
R cuneate lobe	13.27±28.15	84.18±24.05*	74.22±15.11*	82.44±13.81*	6.384	0.001
L fusiform gyrus	88.45±18.12	88.36±15.10	83.44±16.39	75.89±11.14	1.397	0.259
R fusiform gyrus	90.82±13.95	85.55±12.21	85.11±18.51	81.56±13.20	0.701	0.557

L lingual gyrus	94.00±15.05	75.27±16.24*	72.56± 9.28*	74.56±10.35*	5.887	0.002
R lingual gyrus	00.64±23.43	78.09±12.42*	72.00± 9.37*	75.89±15.89*	6.419	0.001

Notes：Post-hoc comparisons (Tukey HSD test) were used to compare the significant regions among the groups using the ANCOVA.

“－” means no significant activation voxel found in the area;

“*” means significant difference when the activation voxels obtained from the other groups (i.e, HnS, HNS, and HLS) were compared with the PDS Group;

“#”means statistical difference between the HNS group and the HLS Group.

Table 3. The cluster szie of the activated voxels (mm^3) in four groups whilst imitating CSL (Mean±SD)

Active Area	PDS Group	HnS Group	HNS Group	HLS Group	*F*	*p*
L middle frontal gyrus	194.27±16.00	188.36±18.52	182.00±20.35	175.33±11.31	2.296	0.094
R middle frontal gyrus	189.18±10.44	186.64±11.76	179.67± 9.42	178.78±13.61	2.023	0.128
L inferior frontal gyrus	285.82±10.78	—	219.44±10.82*	183.78± 5.49*	300.841	0.000
R inferior frontal gyrus	285.27±13.19	—	219.67±14.83*	178.22± 8.69*	185.675	0.000
L superior temporal gyrus	212.55±31.14	—	131.00± 7.16*	—	58.634	0.000
R superior temporal gyrus	210.45±41.44	—	128.78± 6.28*	—	33.996	0.000
L middle temporal gyrus	192.73±16.14	183.27±11.42	180.11± 9.53	178.33±10.81	2.734	0.058
R middle temporal gyrus	185.36±14.89	179.64±12.82	182.89±12.76	176.78±11.76	0.801	0.501
L inferior parietal lobule	177.27±21.11	—	179.33±19.38	—	0.051	0.824
R inferior parietal lobule	185.09±16.65	—	180.11±10.13	—	0.615	0.443
L superior parietal lobule	256.55±13.89	173.18±8.20*	176.44± 8.90*	174.89± 8.77*	166.600	0.000
R superior parietal lobule	270.91± 9.01	172.82±9.10*	176.89± 5.86*	171.89± 8.33*	366.301	0.000
L cuneate lobe	204.09±7.73	187.55±9.73*	177.11±10.81*†	177.33± 6.04*†	21.351	0.000
R cuneate lobe	206.64±7.49	184.64± 9.33*	182.00± 8.93*	183.33±10.89*	17.243	0.000
L fusiform gyrus	177.55±10.39	184.27±19.55	176.44± 8.49	170.33±11.43	1.798	0.165
R fusiform gyrus	183.18±11.27	182.36±14.07	175.11± 7.08	175.44± 8.23	1.603	0.206
L lingual gyrus	188.45±9.41	178.91± 9.12*	173.00± 9.97*	177.78± 9.07*	4.864	0.006
R lingual gyrus	191.55±8.49	179.27± 9.19*	179.78±11.19*	177.89± 5.82*	5.382	0.004
L precentral gyrus	185.64±14.42	178.64±17.70	173.11± 9.35	177.11±11.11	1.444	0.246
R precentral gyrus	181.36± 5.57	177.82± 7.60	173.89± 6.74	173.67± 9.04	2.544	0.071
L paracentral lobule	180.73± 9.67	174.73± 6.89	172.78±13.81	176.89±13.19	0.990	0.408
R paracentral lobule	174.82±15.56	174.64±12.65	169.44±16.01	172.67±12.98	0.292	0.831
L cerebellum	181.00±12.60	178.91±17.39	171.22±14.23	177.00±15.65	0.751	0.529
R cerebellum	183.18±13.39	178.55±17.03	182.78±12.40	174.89± 8.88	0.804	0.500

***Notes*：** Post-hoc comparisons (Tukey HSD test) were used to compare the significant regions among the groups using the ANCOVA.

"—" means no significant activation voxel found in the area;

"*" means significant difference when the activation voxels obtained from the other groups (i.e, HnS, HNS, and HLS) were compared with the PDS Group;

" †"means statistical difference when the activation volexes obtained from the HNS and the HLS groups were compared with the HnS Group (i.e., HnS vs. HNS; HnS vs. HLS).

Appendix 1 Learning outcome:

The reader will understand basic concept of sign language and its neural mechanisms.

Appendix 2 Continue education questions

- **Questions**

Question 1

The description about sign language

1) a special language used primarily by severe hearing impaired people;

2) it conveys meaning using hand shapes only;

3) it has no grammar structure;

4) it is not considered as a natural language.

Answer: 1)

Question 2

The neural basis of sign language perception in deaf people is associated with the activation of secondary auditory cortex. True or False

Answer: True

Question 3

Sign language and spoken language do not share any functional areas in the brain. True or False

Answer: False

Question 4

Which following areas are mainly responsible for sign language acquisition and speech processing

1) Primary frontal area;

2) Broca's area;

3) Wernicke's area;

4) Primary somatosensory area.

Answer: 2) and 3)

Question 5

Which following stimulations can active the auditory cortex?

1) Sound;

2) Vision;

3) Touch;

4) Smell.

Answer: 1), 2) and 3)

Research Highlights

- To assess neural changes in people with different CSL experience/hearing status using fMRI
- Sign language processing appeared to be sensitive to the age of sign language acquisition
- Deaf signers showed significantly greater activated areas in response to CSL.
- Increased activations involved in producing sign language during a task to imitate CSL.

Figure

Figure 1

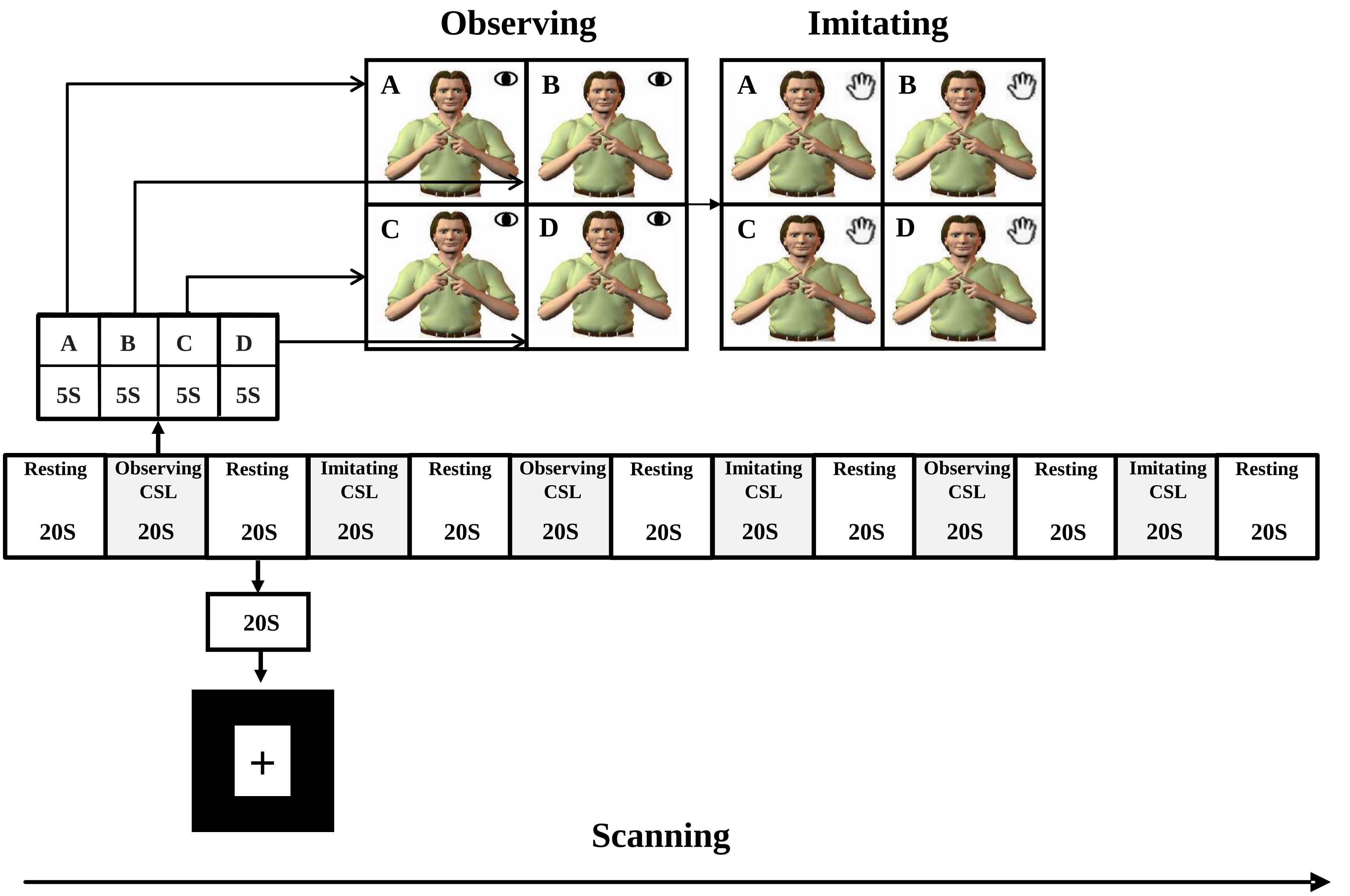
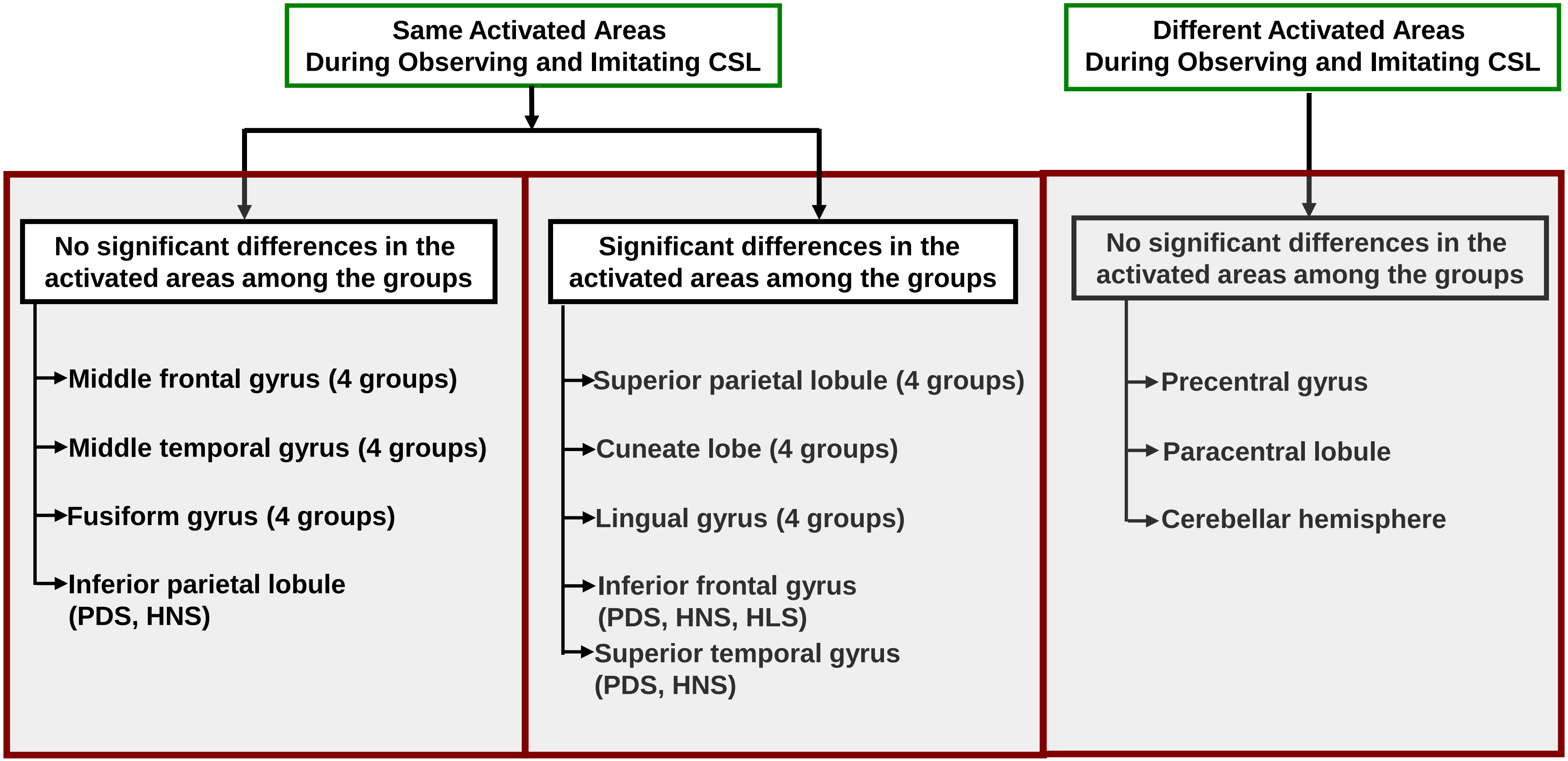


Figure 2



Same Activated Areas
During Observing and Imitating CSL
Different Activated Areas
During Observing and Imitating CSL
No significant differences in the activated areas among the groups
Middle frontal gyrus (4 groups)
Middle temporal gyrus (4 groups)
Fusiform gyrus (4 groups)
Inferior parietal lobule (PDS, HNS)
Significant differences in the activated areas among the groups
Superior parietal lobule (4 groups)
Cuneate lobe (4 groups)
Lingual gyrus (4 groups)
Inferior frontal gyrus (PDS, HNS, HLS)
Superior temporal gyrus (PDS, HNS)
No significant differences in the activated areas among the groups
Precentral gyrus
Paracentral lobule
Cerebellar hemisphere

Figure 3

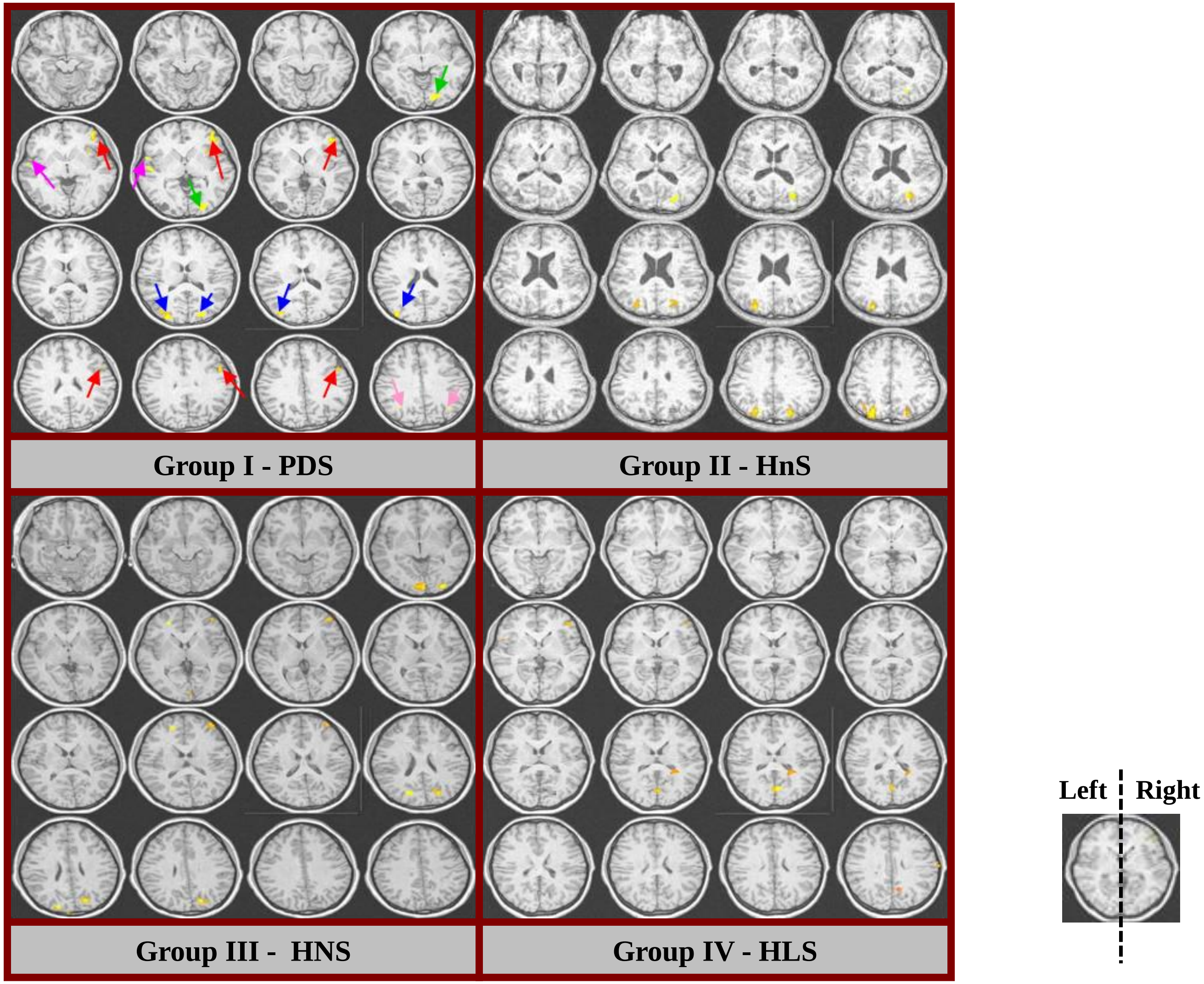


Figure 4