http://www.cjmb.org

doi 10.34172/cjmb.2023.38

Open Access

Original Article

Crescent Journal of Medical and Biological Sciences
Vol. x, No. x, xx 2023, x–x
eISSN 2148-9696

Speed of Auditory Information Processing in Congenitally Blind and Sighted Subjects: A Behavioral and Electrophysiological Study

Mohammad Hosseinabadi[1], Ghassem Mohammadkhani[1*], Arash Almasi[2]

Abstract

Objectives: Blind people must rely more than sighted people on auditory input in order to acquire information about the world. The present study was designed to test the hypothesis that speed of auditory information processing is better in people with congenital blindness compared to sighted people.

Materials and Methods: This study is an applied research and its method is survey research. Sixteen adolescents with congenital blindness participated in the study, together with 16 sighted control adolescents. All participants were evaluated to determine the speed of auditory information processing with two versions of PASAT (Paced Auditory Serial Addition Test) and event-related potentials.

Results: The results using independent t-test showed that blind adolescents with Pasat 1.6 test are significantly different from the group of sighted adolescents and show better performance compared to the sighted group (P = 0.013), but no significant difference was observed between the two groups in PASAT 2.6 (P = 0.38). Also, regarding event related potentials (ERPs), decreasing the latencies and increasing the amplitude of P3 wave in event-related potential showed a significant difference between the blind group and the sighted group.

Conclusions: This study shows that the performance of auditory information processing in blind adolescents is somewhat better compared to sighted adolescents, and the faster the stimuli are presented, the more significant the difference. It is suggested that the education of blind children emphasize the ability of these children to process auditory information.

Keywords: Auditory processing speed, PASAT, Congenitally blind, Event related potential

Introduction

All creatures, including humans, need information from the environment to grow and evolve. The means of obtaining information are special senses such as sense of hearing, sight, touch, etc. These senses do not function fully at birth. Each sensory system needs two components of innate health and appropriate environmental stimulation to achieve maximum function (1). Research shows that people who are deprived of their sense of sight have considerable power and flexibility in their other senses to compensate for this sensory deficiency (2). In everyday life, blind people rely more on auditory information than Sighted people to identify people, localize events, or process language. Among the various senses of the body, it can be said that after the sense of sight, it is the sense of hearing through which man receives the most information from the environment. With the exception of about one-third of blind people who have lost their hearing in addition to their visual impairment, blind people need almost their sense of hearing to understand their surroundings, and given that using their sense of hearing is so important to them, it is necessary to pay attention to environmental sounds and listening skills in these people (3). An increasing number of studies have provided evidence that increased use of the auditory system leads to compensatory auditory behavior in the blind. Auditory functions have different dimensions, one of the most important of which is the speed of auditory information processing. The blind person performs better in auditory functions, such as duration discrimination, information processing speed, as well as in auditory language and memory (4). To evaluate the speed of information processing, researchers try to measure a person's reaction time to specific stimuli. These stimuli can be visual, auditory, tactile, etc. In the auditory field, the response time to the auditory stimulus is used to measure auditory processing speed (5). Other researchers study the speed of information processing by controlling the performance of individuals in response to specific stimuli, using tests such as N-back test and PASAT (Paced Auditory Serial Addition Test) (6,7). The PASAT was primarily developed to assess the effects of traumatic brain injury on cognitive functioning. Subsequent research has shown that the PASAT has clinical utility in detecting auditory cognitive processing in healthy as well as in patients with a wide variety of neuropsychological syndromes (8). These comprehensive data suggest that this task is particularly suitable to investigate and train the speed of auditory information processing and working memory in both, healthy subjects and psychiatric patients (9). At the neural level, cortical event related potentials

Received 10 January 2022, **Accepted** 1 August 2022, **Available online** 26 June 2023

[1]Department of Audiology, School of Rehabilitation, Tehran University of Medical Sciences, Tehran, Iran.
[2]Research Center of Environmental determinants of Health, Kermanshah University of Medical Sciences, Kermanshah, Iran
*Corresponding Author: Ghassem Mohammadkhani, Tel +98-21-77530636, Fax +98-21-77684889, Email: mohamadkhani@tums.ac.ir

Key Messages

- The results of this study show that in people with congenital blindness, due to greater dependence on auditory inputs for communication, the speed of auditory information processing is better than normal people. This performance improvement is more noticeable, especially in difficult hearing conditions (eg, PASAT).

(ERPs), especially the slow cortical N1-P3 sequence, have provided insight into brain processes that underlie many aspects of auditory perception, including frequency, intensity, and duration discrimination (10,11). The results of studies show that latency and amplitude of ERP are a proper way to investigate speed of auditory information (12). A frequently used paradigm in these studies is the "oddball" task, in which participants respond deliberately to infrequent target stimuli, ignoring frequent standards. This paradigm can evaluate the processing of information in the field of auditory. (13).

But contrary to the hypothesis of perceptual compensation, which states that the blind people have a better sense of hearing, some new findings do not find a difference between the auditory function of blind and sighted subjects. They state that blind people do not have special talents in their other senses and what can be said without a doubt is that the learning factor plays an important role in hearing analysis and its function ,and obviously blind people have more experience than sighted people in paying attention to and interpreting auditory information obtained from their environment (14).

Finally, what should be said is that so far little research has been done on the auditory processing speed in blind people, and the research conducted has yielded different results. On the one hand, there is a common belief that the blind people have more power in this area, and on the other hand, some studies deny the existence of such a difference. Therefore, the present study is designed to test the hypothesis that the speed of auditory information processing of congenitally blind is better than sighted subjects. It also seems to be no study on the auditory processing speed in blind people using the PASAT, and this is the first study to use the PASAT and ERP responses.

Materials and Methods

This study is an applied research and its method is survey research, which was done after obtaining approval from the Research Ethics Committee of Tehran University of Medical Sciences (IR.TUMS.FNM.REC.1398.081). The study was also in line with the World Medical Association's Declaration of Helsinki. The steps of the research as well as the possible risks of the electrical stimulation intervention were fully explained to the parents. The parents completed the consent form prepared for this purpose and they were free to leave the study at any stage

Study Sample

Sixteen adolescents with congenital blindness (male=7 and female = 9; mean age: 14.71 ± 0.75 and 14.77 ± 0.97 years, respectively), in the age range of 14-16 years (14.75 ± 0.85 years), and 16 adolescents with normal vision as a control group (male = 7 and female = 9; mean age: 14.28 ± 0.48 and 14.77 ± 0.83 years, respectively), in the age range of 14-16 years (14.56 ± 0.72 years), participated in this study. The samples were selected from middle schools in District 2 of Tehran. Based on inclusion criteria in this study, the evaluation of intellectual function was performed by a psychologist. The participants' verbal IQ score was within the range of 90-132 (107.29 ± 14.28). All participants were monolingual (native Persian speakers) and right-handed (according to the Edinburgh Handedness Inventory) with normal hearing (better than 20 dBHL) at 250–8000 kHz frequencies (15). None of the adolescents had a history of a neurological disease or accompanying neurological disorders. Besides, none of the participants reported any other significant cognitive activity, such as painting or playing music. The demographic characteristics of the two groups participating in the study are described in Table 1.

Experimental Design

To achieve the research goal, in the first step, all participants were tested with versions of PASAT 1/6 and PASAT 2/8. In order to eliminate the effect of learning in the participants, the versions of PASAT were performed in two stages at intervals of one week. In the next step, ERPs were recorded from all participants. All stages of the test were performed between ten and eleven in the morning.

Cognitive Tasks

Auditory Oddball Test

Auditory oddball paradigm is an experimental design used to examine cognitive processes and information processing. Presentations of sequences of repetitive stimuli are infrequently interrupted by a deviant stimulus. The reaction of the participant to this "oddball" stimulus is recorded. In the present study, the subjects were exposed to 150 tones (120 tones at 1000 Hz and 30 tones at 2000 Hz) of 50 ms duration and 5 ms rise/fall time in a random order, with fixed stimulus-onset asynchrony (1100 ms) presented through sound fields at 60 dB SPL. Prior to the experiment, the subjects were familiarized with both tones, and the target (2000 Hz) was introduced. When performing the task, the participants were asked to accurately and quickly press the button with the right

Table 1. Demographic Characteristics of the Blind and the Sighted Groups

Group	Age	Education	Gender		Intelligence
		Middle School	Female	Male	
Blind	14.75 ± 0.85	16	9	7	110
Sighted	14.56 ± 0.72	16	9	7	112

hand and finger thumb when hearing the target stimulus and to refrain from pressing the button when hearing the standard stimulus.

Behavioral Assessment

Paced Auditory Serial Addition Test

The PASAT is a computerized test that shows a scale of cognitive performance that specifically measures the speed and flexibility of processing auditory information using the ability to compute in individuals. This test was originally developed by Gronwall in 1977 to monitor the recovery rate of patients suffering mild traumatic brain injury and later adapted by Rao and colleagues in 1989. They used this test to assess the speed of information processing in multiple sclerosis (MS) patients (16) .The measurements of this test are now widely used for different groups of subjects.

In the PASAT, the rate of presentation of auditory stimuli is adjustable. Numbers (1 to 9) are presented separately every 1.6 seconds (PASAT 1.6) or every 2.8 seconds (PASAT 2.8) to compare people's reaction speeds. The subject must add each new digit to the one immediately prior to it. For example, a person first hears the two digits 5 and 7 and has to say 12, and if the next digit is 3, he has to say 10 and so on. In this test, 61 numbers are presented and the person answers 60. In most performances, the first 10 answers are a kind of exercise. The test result is calculated based on the percentage of correct answers of the person. To reduce the familiarity with stimuli in clinical trials and other consecutive studies, two parallel forms of this test have been developed. The educational differences in this test are very important and therefore the researcher in any research that uses this test should homogenize the educational level of all subjects. Note: Any interfering factor that the examiner believes affects the performance of the subject should be controlled as much as possible, such as noises outside the room, subject fatigue and disregard for test flow.

The validity of this test has been investigated in 101 healthy adults aged 25 to 65 years. In different researches, the reliability of the test has been obtained by using the method of two parallel forms (0.84).

Event Related Potential Recording

ERP was performed with non-verbal stimuli in both groups using with the EBNeuro Sirius electroencephalography (EEG) system (EBNeuro/Florence, Italy) (bandpass 0.01–30 Hz). When recording ERP, the child was asked to sit in a comfortable chair and look at the cartoon images on the monitor screen to avoid muscle artifacts. To reduce waste of time, adolescents' skin was cleansed with 10-20 gels to improve impedance in any condition. The average duration of ERP recording without preparation time was 15 minutes. The electrode impedance and inter-electrode impedance were <5 kΩ and <2 kΩ, respectively. The experiment was performed in an acoustic room without electrical interference.

The response was recorded with Ag-AgCl active electrodes on at midline electrode sites (Fz, Cz, and Pz), reference electrode located on right and left auricle (A1 and A2) and ground electrode on forehead (Fpz) (according to the 10/20 International system (Jasper, 1958). Eye movements were controlled with a bipolar electrode montage (supraorbital to lateral canthus). Also a strict artifact-rejection criterion of 45 mV was used for the cortical recordings.

Data Analysis

Digital filters were used off-line (low pass filter of 30 Hz, high pass filter of 0.1 Hz). The ERP is a sequence of peaks with positive and negative polarity in 200 and 600 ms intervals after stimuli (17). So post-stimulus time was considered 700 ms with pre-stimulus time 100 ms. The positive–negative biphasic waveform cortical-evoked potential elicited by the auditory stimulus displayed P3 wave. The peak analysis was performed at channel Fz. The absolute latency and amplitude of this variable in both groups were identified and analyzed. ERP amplitude were quantified by measuring the baseline-to-peak and latency was defined as time interval between the onset of the stimulus and the appearance of a change in the waveform of auditory evoked potential (18) . A review of auditory oddball studies indicates that the amplitude of P3 wave as an indicator of attention and the cognitive events of stimulus classification, its latency as an indicator of information processing speed can be examined (19).

Statistical Analysis

Data analysis was done with SPSS for Windows, version 24.0 (SPSS Inc., Chicago, IL, USA). In this study, continuous variables were presented as mean ± standard deviation (SD). The normality of data was checked using the Shapiro Wilk test. Independent t-test, was used to compare between groups. All statistical tests were reported with a significance level of 0.05.

Results

Behavioral Data

The descriptive index of correct answers in the tests (PASAT 1.6, PASAT 2.8) in the blind group and the sighted group is shown in Table 2.

The findings were then analyzed using independent t-test to compare the scores of the two groups in each of the two versions of the PASAT. As seen in Table 3, independent *t* test in PASAT 1.6 shows a significant difference between the two groups. So that, the percentage of correct answers is higher in people with congenital blindness (a significant improvement in Speed of auditory information processing) compared with sighted group.

According to the results obtained when the PASAT

Table 2. Percentage of Correct Answers in the Blind and the Sighted Groups in the PASAT

PASAT	Group	
	Blind	Sighted
PASAT 1.6	71.75 ± 10.1	62.18 ± 10.3
PASAT 2.8	77.06 ± 10.7	73.87 ± 9.7

Data are expressed as mean and standard deviation.

Table 3. Independent *T* Test to Compare the Scores of the Two Groups in PASAT1.6 and PASAT2.8

Test	Statistical Index		
	t	df	*P*
PASAT 1.6	2.64	30	0.013
PASAT 2.8	0.87	30	0.38

is presented with a time (1.6) and a comparison of the value of t obtained (2.6) with a degree of freedom of 30 at the level of 0.05, conclude that there is a significant difference between the two groups and the group of blind adolescents performed better than the sighted and the difference between them is significant. When the PASAT is presented with a time of 2.8 and a comparison of the value of t obtained (0.87) and with a degree of freedom of 30 at the level of 0.05, conclude that there is no difference between the two groups, and although here too the group of blind adolescents performed slightly better than the sighted, the difference between them is not significant.

ERP Data

All subjects of the two groups showed P3 wave in response to auditory stimuli. As seen in Table 4, independent t-test shows a significant difference in the mean amplitude of P3 wave between the two groups. The amplitude of P3 wave in the blind group compared to the control group shows a significant increase. Also, independent t-test shows a significant difference in the latency of P3 wave between the two groups. The latency of P3 wave in the blind group compared to the control group showed a significant decrease.

Discussion

The present study, was designed to test the hypothesis that auditory processing speed is better in adolescents with congenital blindness than in sighted adolescents through PASAT (correct responses) and ERPs. The results show that although blind adolescents performed better than sighted adolescents in PASAT 2.8, but this difference in performance was not significant, but in PASAT 1.6, which required faster response from subjects, blind subjects performed significantly better than healthy. What can generally be deduced from these results is that, the performance of blind adolescents in PASAT, is somewhat better compared to sighted adolescents, and the significance of this difference depends on the speed of stimulus presentation. Blind people must rely more than sighted people on auditory input in order to acquire information about the world, this leads to better auditory memory performance. Many studies show that posterior brain areas normally involved in vision, in difficult hearing conditions, participate in auditory processing in the early blind. Therefore, this helps blind people perform better at high speeds of auditory information (20). In a study by Alho et al auditory ERPs were recorded in early blind subjects and sighted controls. The scalp distribution of the processing negativity (PN), the endogenous waves, and amplitude recovery was in the blind posterior to that in the sighted. This shows that posterior brain areas normally involved in vision participate in auditory processing in the early blind (20).

We also used ERPs as a powerful tool in cognitive processing to assess the speed of auditory information processing (21,22). We found significant decreases in the latency and increased amplitude of P3 wave in the electrophysiological test in the blind group compared to the sighted group. These results could be due to the plasticity hypothesis of the brain. Neural flexibility is the ability to reorganize brain neural networks in response to new life experiences. New information or skills acquired through learning or experience cause continuous functional change within the brain (23). Also, neural flexibility can be considered as an ability of chemical and structural of the brain in response to stimuli (24). Many cases of flexibility occur at the synaptic level, while new evidence suggests other situations and levels that play a role in this phenomenon. These levels include dendritic branches and even the formation of new neurons (25). In fact, it has been shown that in adult rats and monkeys, new neurons are formed in the hippocampus of the brain during memory formation (26). Recent research on the human brain has shown that the activities of the early years

Table 4. The Means and Standard Deviations of Peak Amplitudes (μV) and Latencies (ms) for the P3 Component in the Auditory Oddball Task at Fz Electrode in the Two Groups

	Groups		t	df	*P*	Pairwise Comparisons
	Sighted (S)	Blind (B)				
P3A	6.32 ± 1.49	7.33 ± 0.90	2.30	30	0.028	B>S
P3L	359.21 ± 13.19	348.28 ± 19.25	-2.38	30	0.024	S>B

P3L, Latency P3; P3A, Amplitude P3.

of human life can affect the evolution of the developing brain. For example, in adolescents who are congenitally blind or have lost their sight in their later years, it has been shown that the area of the brain that is involved in the sense of hearing is larger than normal in these people (25). In fact, adolescents with congenital blindness use larger areas and more neurons in the cortex to process auditory information than adolescents with normal vision. Nerve firing in these neurons is faster and more synchronous. So, blind people may process hearing information faster than sighted people due to their greater dependence on auditory signals and the unprofessional use of cortical areas of vision.

Although research on the speed of auditory information processing in blind people is very limited through PASAT, the findings of the present study can be supported by some existing research on the hearing ability of similar groups as well as electrophysiological studies on the blind. For example in the last two decades, some behavioral studies, electrophysiology and brain imaging have shown that after people are deprived of their sense of sight, their power and flexibility in other senses increase to compensate for this deficiency.

Consistent with our study on the use of PASAT in auditory processing speed, in a study by Nikravesh et al in patients with aphasia, the results showed that PASAT is a valid and reliable test for assessing working memory and can be used as a practical tool for auditory cognitive processing (9). Also, in a study by Parmenter et al, PASAT was used to assess auditory processing and working memory function in MS patients. Their study confirmed that the PASAT is a good way to evaluate working memory and auditory processing performance. MS patients had poor performance in cognitive processing and working memory compared to the healthy group (27).

Similar to our study, in a study by Dujardin et al, PASAT was used to assess auditory function in Parkinson's disease (PD). Twenty-seven non-demented PD patients early in the course of the disease participated in the study, together with 15 healthy control subjects. All participants performed the PASAT and a set of clinical tasks assessing information processing speed, working memory and executive functions. The result indicated that the PASAT constitute a useful procedure for assessing executive functions and auditory processing in PD (28).

Consistent with the results of our study, in a study, Röder et al examined the hypothesis of compensating for auditory perception after vision deprivation in the blind group compared with the healthy group. Congenitally blind and sighted adults performed an auditory discrimination task. They had to detect a rare target tone among frequent standard tones. Stimuli were presented and the auditory-ERPs to all tones and reaction times to targets were recorded. The results showed that the increase in amplitude of N2 wave is more pronounced in the blind and also the reaction time to the target stimulus is faster than the sighted group (3).

Also in another study, Röder et al show that congenitally blind people perform better than healthy people during auditory language processing. They studied event-related responses from 15 adolescents with congenital blindness and 15 adolescents with healthy sighted. Participants listened to sentences in order to decide after each sentence if it was meaningful or not. Incongruous sentence-final words elicited an N400 effect in both groups. The N400 effect had a left-lateralized fronto-central scalp distribution in the sighted but a symmetric and broad topography in the blind. Furthermore, the N400 effect started earlier in the blind than in the sighted. These results suggest that blind people process auditory language stimuli faster than sighted people and that some language functions may be reorganized in the blind (12).

Conclusions

In the present study, the researcher investigated the speed of auditory information processing among congenital blind adolescents and the results showed that the auditory processing speed of blind subjects is better than the sighted group, and considering that this study is limited to congenitally blind, it is suggested that in future studies, auditory information processing be considered in people who have acquired blindness. Also, since limitations such as small sample size, limitations in measuring instruments and poor cooperation of the blind can affect the generalization of the results of the present study, it is suggested that future research on the sample, with a larger volume and the use of self-assessment questionnaires and fMRI to be performed to solve the problems ahead. Based on the research findings, it is suggested that teachers develop training programs with emphasis on the auditory function of blind adolescents. Ordinary school teachers can also help increase the speed of auditory information processing in sighted students by providing solutions.

Authors' Contribution

Conceptualization: Ghassem Mohammadkhani.
Methodology: Mohammad Hosseinabadi.
Validation: Mohammad Hosseinabadi.
Formal analysis: Mohammad Hosseinabadi.
Investigation: Mohammad Hosseinabadi.
Data curation: Mohammad Hosseinabadi.
Writing–original draft: Mohammad Hosseinabadi.
Writing–review and editing: Arash Almasi.
Visualization: Arash Almasi.
Supervision: Ghassem Mohammadkhani.
Project administration: Ghassem Mohammadkhani.

Conflict of Interests

None.

Funding

The present paper was extracted from the PhD thesis of the first author in Department of Audiology, School of Rehabilitation, Tehran University of Medical Sciences, Tehran, Iran.

References

1. Levtzion-Korach O, Tennenbaum A, Schnitzer R, Ornoy A. Early motor development of blind children. J Paediatr Child Health. 2000;36(3):226-229. doi:10.1046/j.1440-1754.2000.00501.x
2. Arditi A, Holtzman JD, Kosslyn SM. Mental imagery and sensory experience in congenital blindness. Neuropsychologia. 1988;26(1):1-12. doi:10.1016/0028-3932(88)90026-7
3. Röder B, Teder-Sälejärvi W, Sterr A, Rösler F, Hillyard SA, Neville HJ. Improved auditory spatial tuning in blind humans. Nature. 1999;400(6740):162-166. doi:10.1038/22106
4. Raz N, Willerman L, Yama M. On sense and senses: intelligence and auditory information processing. Pers Individ Dif. 1987;8(2):201-210. doi:10.1016/0191-8869(87)90175-9
5. Tombaugh TN. A comprehensive review of the paced auditory serial addition test (PASAT). Arch Clin Neuropsychol. 2006;21(1):53-76. doi:10.1016/j.acn.2005.07.006
6. Wiens AN, Fuller KH, Crossen JR. Paced auditory serial addition test: adult norms and moderator variables. J Clin Exp Neuropsychol. 1997;19(4):473-483. doi:10.1080/01688639708403737
7. Gonçalves VT, Mansur LL. N-Back auditory test performancein normal individuals. Dement Neuropsychol. 2009;3(2):114-117. doi:10.1590/s1980-57642009dn30200008
8. Tombaugh TN. A comprehensive review of the paced auditory serial addition test (PASAT). Arch Clin Neuropsychol. 2006;21(1):53-76. doi:10.1016/j.acn.2005.07.006
9. Nikravesh M, Jafari Z, Mehrpour M, et al. The paced auditory serial addition test for working memory assessment: psychometric properties. Med J Islam Repub Iran. 2017;31:61. doi:10.14196/mjiri.31.61
10. Finney EM, Fine I, Dobkins KR. Visual stimuli activate auditory cortex in the deaf. Nat Neurosci. 2001;4(12):1171-1173. doi:10.1038/nn763
11. Giard MH, Lavikahen J, Reinikainen K, et al. Separate representation of stimulus frequency, intensity, and duration in auditory sensory memory: an event-related potential and dipole-model analysis. J Cogn Neurosci. 1995;7(2):133-143. doi:10.1162/jocn.1995.7.2.133
12. Röder B, Rösler F, Neville HJ. Event-related potentials during auditory language processing in congenitally blind and sighted people. Neuropsychologia. 2000;38(11):1482-1502. doi:10.1016/s0028-3932(00)00057-9
13. Núñez Castellar EP, Antons JN, Marinazzo D, Van Looy J. Mapping attention during gameplay: assessment of behavioral and ERP markers in an auditory oddball task. Psychophysiology. 2019;56(7):e13347. doi:10.1111/psyp.13347
14. Abel SM, Figueiredo JC, Consoli A, Birt CM, Papsin BC. The effect of blindness on horizontal plane sound source identification. Int J Audiol. 2002;41(5):285-292. doi:10.3109/14992020209077188
15. Margolis RH, Moore BC. AMTAS®: automated method for testing auditory sensitivity: III. sensorineural hearing loss and air-bone gaps. Int J Audiol. 2011;50(7):440-447. doi:10.3109/14992027.2011.575085
16. Friedova L, Rusz J, Motyl J, et al. Slowed articulation rate is associated with information processing speed decline in multiple sclerosis: a pilot study. J Clin Neurosci. 2019;65:28-33. doi:10.1016/j.jocn.2019.04.018
17. Vaughan HG Jr, Ritter W. The sources of auditory evoked responses recorded from the human scalp. Electroencephalogr Clin Neurophysiol. 1970;28(4):360-367. doi:10.1016/0013-4694(70)90228-2
18. Hillyard SA, Picton TW. On and off components in the auditory evoked potential. Percept Psychophys. 1978;24(5):391-398. doi:10.3758/bf03199736
19. Barry RJ, De Blasio FM. Performance and ERP components in the equiprobable go/no-go task: Inhibition in children. Psychophysiology. 2015;52(9):1228-1237. doi:10.1111/psyp.12447
20. Alho K, Kujala T, Paavilainen P, Summala H, Näätänen R. Auditory processing in visual brain areas of the early blind: evidence from event-related potentials. Electroencephalogr Clin Neurophysiol. 1993;86(6):418-427. doi:10.1016/0013-4694(93)90137-k
21. Gori M, Amadeo MB, Campus C. Spatial metric in blindness: behavioural and cortical processing. Neurosci Biobehav Rev. 2020;109:54-62. doi:10.1016/j.neubiorev.2019.12.031
22. Teder W, Näätänen R. Event-related potentials demonstrate a narrow focus of auditory spatial attention. Neuroreport. 1994;5(6):709-711. doi:10.1097/00001756-199402000-00012
23. Bavelier D, Neville HJ. Cross-modal plasticity: where and how? Nat Rev Neurosci. 2002;3(6):443-452. doi:10.1038/nrn848
24. Merabet LB, Pascual-Leone A. Neural reorganization following sensory loss: the opportunity of change. Nat Rev Neurosci. 2010;11(1):44-52. doi:10.1038/nrn2758
25. Cohen LG, Celnik P, Pascual-Leone A, et al. Functional relevance of cross-modal plasticity in blind humans. Nature. 1997;389(6647):180-183. doi:10.1038/38278
26. Kaas JH, Qi HX, Burish MJ, Gharbawie OA, Onifer SM, Massey JM. Cortical and subcortical plasticity in the brains of humans, primates, and rats after damage to sensory afferents in the dorsal columns of the spinal cord. Exp Neurol. 2008;209(2):407-416. doi:10.1016/j.expneurol.2007.06.014
27. Parmenter BA, Shucard JL, Benedict RH, Shucard DW. Working memory deficits in multiple sclerosis: comparison between the n-back task and the paced auditory serial addition test. J Int Neuropsychol Soc. 2006;12(5):677-687. doi:10.1017/s1355617706060826
28. Dujardin K, Denève C, Ronval M, et al. Is the paced auditory serial addition test (PASAT) a valid means of assessing executive function in Parkinson's disease? Cortex. 2007;43(5):601-606. doi:10.1016/s0010-9452(08)70490-8