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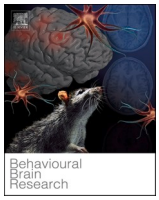

Research article

A cross-sectional study of the event-related potential of tactile stimulus recognition and brain activity in individuals with early- and late-onset visual impairment

Mónica Ahulló [a], M.Luz Sánchez-Sánchez [b,*], Elena Ortiz-Teran [c,d], Tomás Ortiz [c], Enrique Varela-Donoso [a]

[a] Department of Physiotherapy, Faculty of Nursing, Physiotherapy and Podiatry, Complutense University of Madrid, 28040, Madrid, Spain
[b] Physiotherapy in Motion, Multispeciality Research Group (PTinMOTION), Department of Physiotherapy, University of Valencia, 46010, Valencia, Spain
[c] Department of Legal Medicine, Psychiatry and Pathology, Faculty of Medicine, Complutense University of Madrid, 28040, Madrid, Spain
[d] Department of Economics, Faculty of Economics and Business, Universidad Antonio de Nebrija, 28015, Madrid, Spain

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ABSTRACT

People with visual impairment (VI) may have improved tactile recognition skills due to enhanced cognitive processing. However, whether this enhancement varies depending on whether VI is acquired early or late is unclear. This study aimed to determine the differences in behavioral performance during tactile stimulus detection and P300 wave latency between three groups: early-onset VI group (EVI), late-onset VI group (LVI), and sighted control group (CG). Brain cortical activity was also analyzed. Participants' hands were passively stimulated with a vibrotactile device, and participants were asked to identify the stimulus while electroencephalography and P300 event-related potentials were recorded. Behavioral performance, P300 latency, and bioelectrical brain activity were assessed. EVI ($n = 13$) and LVI ($n = 12$) groups showed better tactile recognition performance with shorter reaction times than CG ($n = 14$) ($p < 0.05$). This may be due to the tactile experience that people with VI may have. No differences were found among the three groups for P300 latency ($p > 0.05$). Both EVI and CG groups exhibited significant activity in the superior and middle frontal regions, which may be related to attention and working memory processes. EVI group also exhibited greater activity in bilateral parietal structures, which may be linked to multimodal information processing and the dorsal pathway, involved in spatial processing (the "where" of things). By contrast, the LVI group showed significantly higher activity in the superior temporal areas, which may be related to the ventral pathway responsible for object identification (the "what" of things).

1. Introduction

The human brain has the ability to acquire, process, store, and retrieve information to understand its environment and behave appropriately in different life situations [1,2]. Much of this is due to neuroplasticity—the brain's ability to be flexible and remodel its connections in different ways in response to intrinsic and extrinsic factors [3,4]. Neuroplasticity is key to understanding the learning process, and it has been extensively studied in the context of brain damage [5], as well as after damage to a sensory system, such as after vision loss [6,7].

Visual impairment (VI), which encompasses total blindness and varying degrees of vision loss, is one of the most prevalent disabilities worldwide [8]. Approximately one billion people worldwide have a VI that could have been prevented or has not yet been treated [9]. The causes of VI are varied and include conditions like glaucoma, diabetic retinopathy, cataract, and macular degeneration [9], all of which are closely associated with aging [10]. By 2050, the number of adults over the age of 50 with a VI is expected to double as the population ages [11]. Not only does VI have a significant impact on the global economic burden [12], but it also has an impact on the personal sphere. VI implies

* Correspondence to: Physiotherapy in Motion, Multispeciality Research Group (PTinMOTION), Department of Physiotherapy, University of Valencia, C/ Gascó Oliag nº 5, Valencia 46010, Spain.
E-mail addresses: mahullo@ucm.es (M. Ahulló), M.Luz.Sanchez@uv.es (M.Luz Sánchez-Sánchez), eortizte@nebrija.es (E. Ortiz-Teran), tortiz@ucm.es (T. Ortiz), evarelah@ucm.es (E. Varela-Donoso).

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a significant reduction in these people's quality of life, especially those with more severe forms of VI, such as a severe deficit or total blindness [13,14]. For this reason, boosting the resources that will help them compensate for the deficits caused by their visual condition is essential [15].

The brain tries to develop compensating mechanisms to offset some of the deficits caused by sensory loss [16]. Traditionally, it has been widely accepted that individuals with VI enhance their skills in their remaining senses [17,18], and this has mainly been linked to reorganization of brain activity patterns [19,20]. Greater compensation tends to occur in the sense of touch [17], likely due to its critical role in human socialization and survival [21]. In fact, individuals with VI have been found to have superior tactile skills to compensate for their vision loss. [22]. This enhancement can be explained by the compensatory hypothesis [23], which suggests that the absence of sensory input in one modality (such as vision) can lead to improvement in cognitive-related functions by recruiting non-visual neurons [24,25]. Indeed, research reports that individuals with VI perform better on a wide range of cognitive tasks [26].

A study of the relationship between tactile performance and cognitive processing in the VI population would be of interest, particularly from an electrophysiological perspective [20,27]. Due to its resolution in milliseconds (ms), electroencephalography (EEG) is one of the most widely used techniques for studying psychological and brain activity processes [28], and can be used in conjunction with event-related potentials (ERPs) to explore cognitive processes following a specific stimulus presentation [29]. ERPs have been used in previous studies to analyze patterns of brain activity and task performance in people with VI [30,31]. Among the various ERP components, the P300 wave has received considerable attention in research [29]. This wave is significant because it is associated with cognitive processes, mainly attention and working memory [32]. However, to the best of our knowledge, only two studies have examined this ERP component in subjects with VI [33,34]. These studies did not compare individuals who acquired VI early in life versus those who acquired it later, leaving it unclear whether there are any differences between these groups. Furthermore, it remains uncertain whether the age at which VI begins affects tactile performance, possibly due to variations in accumulated tactile experience. Some researchers suggest that individuals with early-onset VI exhibit better tactile performance than those with late-onset VI [30,35,36]. Conversely, some studies indicate that individuals with late-onset VI perform better [37, 38] or equally well in tactile tasks compared to individuals with early-onset VI [39]. Given that individuals with VI are thought to gain more experience in recognizing non-visual stimuli, such as tactile inputs [22], and that this may be attributed to enhanced cognition processing [24,25,40], a more in-depth understanding of these factors could be clinically relevant for designing rehabilitation programs and interventions aimed at improving the capabilities of individuals with VI.

To address this gap, the main objective of the present study was to determine whether there are differences in the performance of recognizing passive tactile stimuli between sighted subjects and individuals with early-onset and late-onset VI, as well as in the P300 wave latency. Additionally, we aimed to assess the activation of cortical brain areas in sighted individuals and people with early-onset and late-onset VI, while recognizing tactile stimuli. We hypothesized that individuals with early and late-onset VI would have better tactile recognition performance due to their greater tactile experience, as well as lower P300 latencies compared to sighted people, owing to improved cognitive data processing. Finally, each of the three groups was expected to show a different pattern of cortical brain activation while carrying out a simple tactile recognition task.

2. Material and methods

2.1. Design and participants

This cross-sectional study complements the findings of previous research [41]. The sample comprised 39 participants: 25 individuals with a VI and 14 age-matched individuals without a VI, who belonged to the control group (CG). Participants with VI had to be previously diagnosed by a physician, with a degree of vision classified as severe VI or total blindness [42], as verified by the researchers through a medical report provided by the participant [43]. Since our purpose was to detect the changes that occur with early and late vision loss, participants with VI should have lost their vision at 5 years of age or earlier or at 14 years of age or later, as done in previous studies [22,44], and based on the developmental stages of the anatomical brain region for V1 [45]. Thus, participants with VI were classified into two groups: the early-onset VI group (EVI) for vision loss occurring at or before 5 years of age and the late-onset VI group (LVI) for vision loss occurring at or after 14 years of age.

Purposive sampling was used to select participants over a 2-month period. CG participants were recruited from the staff of the authors' institution and the family members of participants with VI, while EVI and LVI participants were recruited from different associations of people with vision loss, as well as from different universities located in Madrid, Spain.

The inclusion criteria for the three groups required participants to be between 18 and 60 years of age and able to understand simple verbal instructions. The exclusion criteria encompassed vestibular, psychiatric, or sensorimotor disorders, as well as brain damage such as cortical blindness and any disease that may affect the brain, including stroke, multiple sclerosis, and other neurological conditions. All participants were informed of the objectives and procedures of the study, both verbally and in writing. Those who met the selection criteria and wanted to participate signed the informed consent. Then, to ensure their anonymity, each participant was assigned a numerical code. The Institutional Review Board of the San Carlos University Hospital Ethics Committee in Madrid (Spain) approved the procedures of the present research (20/071-E_Tesis), which complied with the Declaration of Helsinki [46]. To conduct this study, we followed the suggestions outlined in the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines [47].

2.2. Procedures

The participants were evaluated at the Tactile Vision Laboratory, located at the Department of Legal Medicine, Psychiatry and Pathology of the Complutense University of Madrid. All participants were interviewed about their sociodemographic characteristics. In addition, EVI and LVI participants answered questions about their vision, rehabilitation, and mobility characteristics. The participants also performed the tactile recognition task, during which behavioral measures (reaction time, number of correct and incorrect responses), and relevant P300 wave data were collected.

2.2.1. Tactile stimulation system

As displayed in Fig. 1, we used a tactile stimulation system consisting of two main components: a tactile stimulator device and a keyboard [48]. The purpose of the tactile stimulator was to stimulate the skin of the left participant's hand. This device was piezoelectric and featured 32 horizontal lines and 48 vertical lines, providing a total of 1536 tactile points. Each point was covered with a nylon tip designed to enhance the vibrotactile stimuli experienced by the participant's skin. The touch points were spaced 2 mm apart. Micromotors were used to raise points, creating either vertical or horizontal lines and providing vibrotactile feedback. Each stimulation point operated independently, allowing us to create the desired shapes (horizontal or vertical lines). In this setup, each

Fig. 1. Tactile Stimulation System. The image shows the tactile stimulator on the left and the pulsatile keyboard on the right.

line measured 0.5 cm in width and 5 cm in length, presented in the center of the stimulator. Each vibrotactile stimulus, in the form of a line, was presented at a rate of one per second [31]. In addition, the keyboard was equipped with a pulsatile button. When the participant pressed the button with their other hand, the keyboard sent a behavioral response to a software program, which recorded this motor response. The stimulation system was employed to carry out the protocol of the stimulation task, which is described in the following sections.

2.2.2. Tactile stimuli recognition task

Participants completed a single five-minute session of a tactile recognition task in a room isolated from external noise and in complete darkness. The room was equipped with an armchair and a table on which the stimulation system was placed. The participant was asked to sit on the armchair, place the palm of their left hand on the stimulation matrix, and touch the pulsatile button with their right hand. The participant was then asked to close their eyes, at which point the stimulation process began [31,41]. According to the Oddball Paradigm, the tactile stimulator randomly projected horizontal (20 %) or vertical (80 %) lines onto the center of the participant's palm. Thus, of the 300 stimuli presented at a rate of one per second, 60 were horizontal lines and 240 vertical lines. Therefore, the stimulator actively touched the skin of the subject, and all tactile stimuli received by the participants were applied passively (passive touch) [34]; that is, the participant let the stimulator touch his/her stationary hand. Each line was presented for 300 ms at a frequency of 40 hertz (Hz), which is in line with the firing frequency of thalamocortical connections [49,50]. Following this, there was a 700-ms interval without any presentation, during which the participant could decide whether to press the button and provide a behavioral response. Thus, the interval between stimuli was 1000 ms.

To elicit the P300 wave, the participant had to actively engage in the task of identifying the target stimulus [29]. Therefore, the participant was asked to press the button with their right hand (motor behavioral response) as soon as they detected the appearance of a horizontal line (low-frequency stimulus) in the palm of their left hand [31]. Such behavioral responses allowed us to obtain information about reaction times, as well as the number of correct and incorrect responses, not considering omissions [31]

2.2.3. Electrophysiology and source localization reconstruction

During the tactile recognition task, a positive polarity wave with a 300-ms delay (P300) of the ERP was recorded using the Neuroscan electrode cup and the high-density (64-channel) ATI EEG system. Reference electrodes were placed on the bilateral mastoids. Additional electrodes were placed on the left and right superior and inferior orbits and the right and left lateral canthi of the eyes to monitor eye movement. The recording epoch lasted 1000 ms (100 ms before the stimulus and 900 ms after the stimulus). The 100-ms pre-stimulus average voltage was defined as the baseline.

As in previous research [48], the data were acquired at a sampling rate of 1000 Hz and analyzed with a band-pass filter of 0.05–30 Hz and a 50-Hz notch filter. Impedances were kept under 10 kOhms [31,51]. Notably, the detection of muscle contractions and artifacts was performed directly offline via a visual inspection of the EEG waves of each subject. This inspection was carried out using three EEG recording analysis systems. First, we performed a spatial interpolation on the entire electrode recording to address noise [52]. Second, we conducted another spatial interpolation in the selected windows, using the electrodes Fp1, Fp2, F3, F4, F7, and F8 as references [52]. Third, in the windows selected for digital analysis, we applied spatial interpolation on the electrodes that exceeded four standard deviations [53]. The interpolated electrodes accounted for no more than 0.4 % of the total. Consequently, before processing and analyzing the ERP average data, all possible signal disturbances were removed. Moreover, moderate linear interpolation of adjacent clean channels was used to replace noisy channels [53]. For the remaining trials without artifacts, the mean values were calculated for each participant [31,48].

The brain sources were localized using the EEG inverse problem with Bayesian model averaging [54]. The individual models were obtained using low-resolution electromagnetic tomography (LORETA) [55]. The next step was to use the Statistical Parametric Mapping (SPM8) software to constrain each model to a specific anatomical region [56,57]. Importantly, 18 areas of the cerebellum and eight areas with less than 10 voxels were excluded from the analysis. The P300 wave was obtained 250–400 ms after the trigger, and analysis of a 40-ms time window of −20 to + 20 ms from the highest positive amplitude peak measured with the PZ electrode [34].

2.3. Statistics

Analysis of the sociodemographic data, VI characteristics, reaction times, number of correct and incorrect responses, and P300 latency was performed using the IBM SPSS Statistics software (v.23.0; IBM Corp, Armonk, NY, USA). All the data were expressed as frequency, mean ± standard deviation, and median [25 and 75 percentiles]. The normality of the data was checked using the Shapiro–Wilk test. The data on the sociodemographic variables among the three study groups were analyzed using one-way analysis of variance (ANOVA), chi-squared or Fisher's exact test, depending on whether the variable was quantitative or nominal. As for the variables related to VI characteristics, these were compared between EVI and LVI using Student's *t*-test, the Mann–Whitney *U* test, or Fisher's exact test as appropriate. Finally, one-factor ANOVA or the Kruskal–Wallis test was used to compare the groups' parameters of reaction time, number of correct and incorrect responses, and P300 latency, depending on whether the data were normally distributed or not. When statistically significant differences were found, pairwise comparisons were performed using Tukey's test. Statistical significance was defined as $p < 0.05$.

Regarding source localization, the LORETA calculations were performed using the SPM8 software [56,57], as previously mentioned. Calculation based on the voxel-by-voxel independent Hotelling's T^2 test against zero was first applied to each participant and then averaged across the group to see where the greatest group activity occurred. Inferential statistics were performed to calculate the *p*-value from Hotelling's T^2 statistic, which was obtained by transforming Hotelling's T^2 statistic into an F statistic. Based on the expected threshold of false positives, the resulting probability maps between statistically significant tests were constrained to a false discovery rate, $q = 0.05$ [58], so that the brain areas with a significance level < 0.05 were displayed in warm colors (from yellow to red) by the software. Lastly, cortical projections were visualized using Caret software [59], in accordance with the coordinate system of the Montreal Neurological Institute [60] and the average atlas of the Montreal Anatomical Institute [56]. The obtained data were presented as 3D activation images superimposed on the average brain [31].

The GRANMO program (version 7.12, April 2012) was used to estimate the sample size, taking into account information about the reaction time variable provided by a previous study [48]. Accepting an alpha risk of 0.05 and a statistical power greater than 0.8 in a two-tailed test, 11 subjects were required in each group to detect a statistically significant minimum difference of 37.2 units between pairs of groups, assuming there were three groups. A common standard deviation of 25.9 was estimated, and the estimated follow-up loss rate was 0 %.

3. Results

A total of 71 individuals with VI and 19 sighted control individuals responded to the call to participate in the study. Ultimately, 25 participants with VI and 14 sighted controls met the selection criteria, completed all the tests, and were included in the sample for this study (Fig. 2).

3.1. Sample characteristics

EVI included 13 participants (mean age of 42.00 ± 11.05 years), while LVI consisted of 12 participants (mean age of 42.17 ± 11.95). CG, with 14 participants, had a mean age of 41.64 ± 10.43 years. As seen in Table 1, no statistically significant differences were found between the three study groups for any of the sociodemographic variables. Except for the variable of time living with VI (T [23] = 5.96, $p < 0.001$), no significant differences between EVI and LVI for other variables related to their visual, mobility, and rehabilitation characteristics were identified ($p > 0.05$).

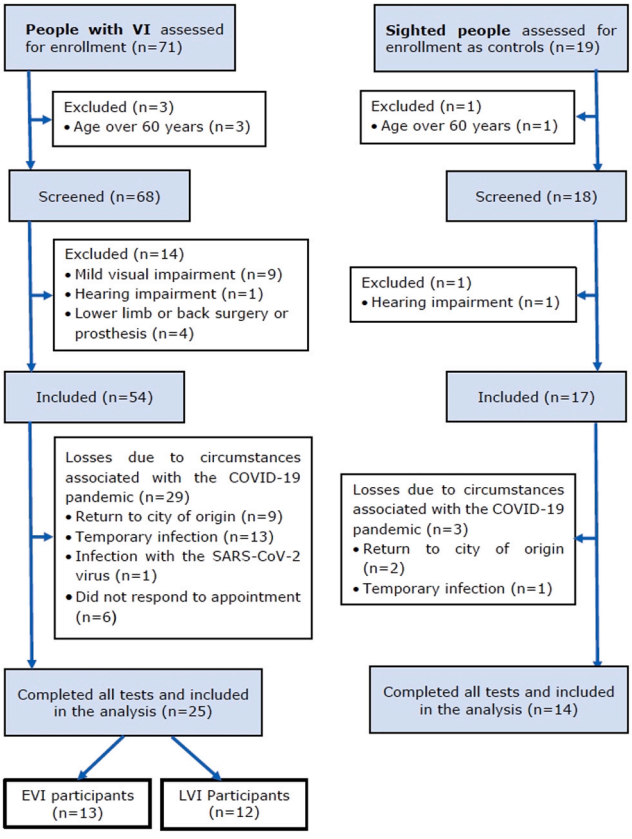

Fig. 2. The STROBE flow chart of the study. The image illustrates the participant selection process and shows the number of individuals included in each group. VI: visual impairment; EVI: early-onset visual impairment; LVI: late-onset visual impairment.

Table 1
Sociodemographic characteristics of the three study groups and the variables related to visual impairment in the early- and late-onset visual impairment groups.

	Groups			
Variables	**EVI (n = 13)**	**LVI (n = 12)**	**CG (n = 14)**	***p***
Sociodemographic				
Sex, m n (%)	8 (61.5)	7 (58.3)	6 (42.9)	0.667[a]
Age	42.00 ± 11.05	42.17 ± 11.94	41.64 ± 10.43	0.992[b]
Educational level (%)				
University education	7 (53.8)	9 (75.0)	11 (78.6)	0.345[a]
Secondary education or VT	5 (38.5)	2 (16.7)	3 (21.4)	
Primary education	0 (0)	1 (8.3)	0 (0)	
No formal education	1 (7.7)	0 (0)	0 (0)	
Visual impairment	**EVI (n = 13)**	**LVI (n = 12)**		***p***
Mobility				
White cane/guide dog	12 (92.3)	11 (91.7)		1.000[c]
Sighted guide	1 (7.7)	1 (8.3)		
Type of VI				
Total Blindness	10 (76.9)	9 (75.0)		1.000[c]
Severe VI	3 (23.1)	3 (25.0)		
Rehabilitation program				
Yes	10 (76.9)	3 (23.1)		1.000[c]
No	10 (83.3)	2 (16.7)		
Time living with VI	40.85 ± 10.56	15.50 ± 10.68		**< 0.001**[d]
Rehabilitation (months)	5.00 [1.00;9.50]	3.00 [1.00;3.00]		0.225[e]

Data are presented as mean ± standard deviation; median and interquartile range [percentile 25; percentile 75] (Mdn [IQR]) or as frequency and percentage (n (%)). Statistically significant differences are highlighted in bold. VI: Visual impairment; EVI: early-onset visual impairment; LVI: late-onset visual impairment; CG: Control Group; VT: Vocational Training. It was considered as statistically significant when $p < 0.05$.

[a] Association between variables calculated with chi-squared test.
[b] Contrast carried out with the one-factor analysis of variance (ANOVA test).
[c] Association between variables calculated with Fisher's exact test.
[d] Contrast carried out with the T-Student's test.
[e] Contrast carried out with the Mann–Whitney U test.

Table 2
Behavioral measures and P300 latency results.

	Groups			
VARIABLES	**EVI (n = 13)**	**LVI (n = 12)**	**CG (n = 14)**	***p***
Correct responses (n)	45.00 [39.50;48.00]	41.50 [37.00;43.75]	39.50 [32.75;42.50]	0.106[a]
Incorrect responses (n)	1.00 [0.00;2.00]	1.00 [0.00;4.75]	2.00 [1.00;4.25]	0.211[a]
Reaction time (ms)	564.51 ± 50.63	604.09 ± 45.16	680.20 ± 78.30	**< 0.001**[b] **< 0.001**[1] **0.008**[2]
P300 Latency (ms)	318.85 ± 33.03	304.50 ± 36.51	315.14 ± 32.67	0.557[a]

Data are presented as mean ± standard deviation; median and interquartile range [percentile 25; percentile 75] (Mdn [IQR]) or as frequency and percentage (n (%)). Statistically significant differences are highlighted in bold. VI: Visual impairment; EVI: early-onset visual impairment; LVI: late-onset visual impairment; CG: Control Group; It was considered as statistically significant when $p < 0.05$.

[1]EVI and CG comparison.
[2]LVI and CG comparison.
[a] Contrast performed with the Kruskal-Wallis test.
[b] Contrast performed with the ANOVA test between subjects. Pairwise comparisons were performed using the Tukey's test.

3.2. Tactile recognition performance and P300 latency

Table 2 displays the behavioral and P300 wave latency results for the three groups. EVI ($p < 0.001$) and LVI ($p = 0.008$) had significantly shorter reaction times than CG ($F[2] = 12.597$, $p < 0.001$, $\eta_p^2 = 0.41$). Although the differences were not statistically significant, EVI and LVI had a higher number of correct responses and a lower number of incorrect responses (Table 2).

Additionally, the overall average brain waveforms synchronized to the passive tactile line stimulus were characterized by a P300 component of ERPs between 250 and 400 ms, as displayed in Fig. 3. Analysis of the P300 revealed no statistically significant differences in latency between the three study groups (Table 2).

3.3. Brain activity

Fig. 4 and Table 3 show the statistically significant localization sources in each group, along with the intensity of activation. When comparing the EEG responses using Hotelling's T^2 test, significant differences in brain activation were found in the P300 component. CG had higher statistically significant activity in the superior and middle frontal left regions. However, EVI showed higher statistically significant activity in the bilateral parietal and frontal areas, while LVI displayed higher statistically significant activity in the bilateral superior temporal zones.

4. Discussion

4.1. Reaction time

The results of the present study show that EVI and LVI individuals have shorter reaction times than CG individuals. Therefore, our study confirms that individuals with VI respond faster to tactile recognition tasks. Furthermore, EVI and LVI participants tended to have more correct and fewer incorrect answers than CG participants. These findings are consistent with those of many other studies [31,48,51,61–64] and, along with recent research on auditory stimulus detection [65], provide mounting evidence that individuals with VI outperform sighted subjects in discriminating non-visual stimuli. These behavioral results may be explained by the fact that individuals with VI, regardless of whether their vision loss occurred early or late in life, have more experience with tactile discrimination tasks [31,66], as they rely on this sense daily to gather information from their environment [22]. As a result of the tactile experience gained, the reaction time to the presented stimulus decreases [67].

We should also pay special attention to the lack of differences in reaction time between EVI and LVI, as this is in line with our initial hypothesis. Reaction time is the most widely used measure of sensorimotor performance in neuroscience and psychology [68,69]. In this

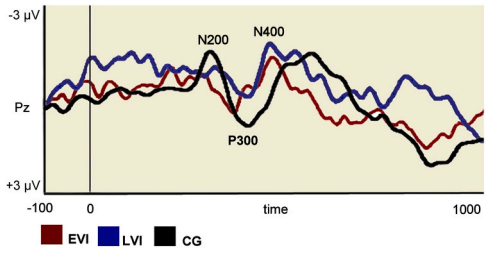

Fig. 3. P300 waveform observed at the Pz electrode in the three study groups. Synchronized brain response to rare stimuli, characterized by a waveform complex. This response begins with a low-amplitude negative wave (N200), followed by a high-amplitude positive wave (P300), and concludes with a low-amplitude negative wave (N400), representing the tactile evoked potential at Pz in the three groups. EVI: early-onset visual impairment; LVI: late-onset visual impairment; CG: control group.

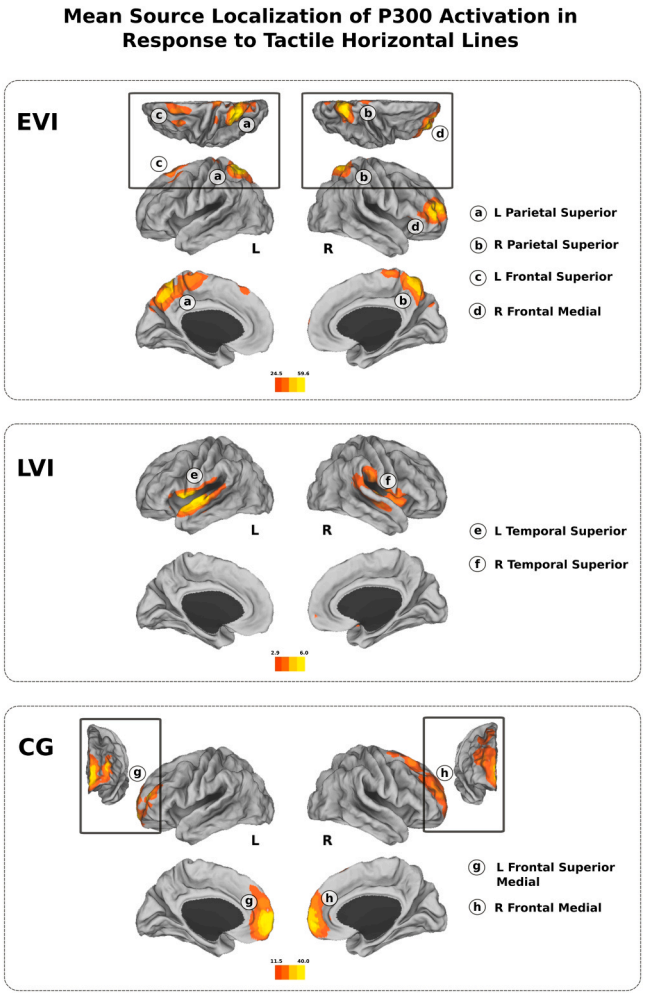

Fig. 4. The P300 mean source localization activation for tactile horizontal lines in the early-onset visual impairment group (EVI), the late-onset visual impairment group (LVI), and the control group (CG). Yellow shading denotes the brain areas in each group with the highest statistically significant bioelectrical activity. L: Left. R: Right.

regard, Noppeney [70] points out that people with early-onset VI would have enhanced sensorimotor skills and more pronounced brain changes than people with late-onset VI—which is also supported by Lazzouni and Leporé [22]. Nevertheless, these studies do not specifically address the reaction time variable but rather mention improvements in other tactile aspects, such as lower tactile thresholds and improved spatial tactile resolution. Moreover, reaction time has been shown to improve with experience [68,69], and individuals with VI have more experience recognizing non-visual stimuli [22] because they rely on touch to recognize their environment daily, regardless of whether vision loss occurs early or late in life.

4.2. P300 latency

The P300 wave latency results suggest that the improvements in reaction time do not appear to be related to an increased cognitive processing speed of information due to VI, thereby providing new evidence to the scarce literature on this topic [33,34], and aligning with previous research findings [34]. The absence of differences in P300 latency between EVI and LVI participants may indicate that early vision loss does not necessarily lead to faster cognitive processing of information, as P300 latency is an established indicator of cognitive processing [71]. Consequently, both EVI and LVI participants may exhibit similar cognitive processing efficiency in response to presented stimuli

Table 3
Main neuroanatomical structures according to projection areas of maximal intensity P300 in three groups.

Group	aal	BA	X	Y	Z	Hotelling's T^2	F-Statistic	*p*-value
EVI	Parietal Superior L	7	-18	-63	60	30,895	9.56	.002
	Parietal Superior R	7	6	27	56	33,987	10.51	.01
	Frontal Superior L	8	-20	19	56	33,631	10.40	.001
	Frontal Medial R	10	35	58	7	33,891	10.47	.001
LVI	Temporal Superior L	48	-50	2	-4	9090	2.81	.05
	Temporal Superior R	48	53	-3	-4	9810	2.97	.04
CG	Frontal Superior Medial L	10	-2	57	-1	32,952	8.31	.001
	Frontal Medial R	10	4	60	1	16,989	8.46	.005

aal: Anatomical Atlas label corresponding to Probabilistic Brain Atlas; BA: Brodmann areas; X, Y, Z: coordinates from Probabilistic Brain Atlas in three spatial axes; T^2: Hotelling statistical test ($p < .05$); EVI: early-onset visual impairment; LVI: late-onset visual impairment; CG: Control Group; L: Left; R: Right.

[72,73]. In a tactile discrimination task such as the one performed in our study, reaction time serves as an important measure reflecting how somatosensory areas process tactile information and convert it into a motor action [74], such as pressing a button. The shorter reaction times observed in VI participants might suggest greater experience in discriminating tactile stimuli. However, tactile discrimination involves not only somatosensory processing, but also cognitive control, selective attention, and decision-making regarding the received information [75–79]. These cognitive processes are common to all humans, regardless of their visual abilities. In this sense, the P300 wave is considered an endogenous or cognitive ERP. As such, it provides information about how data are processed and how the attended stimulus is evaluated [29]. In particular, the P300 component emerges as a result of attention-controlled access to working memory for subsequent information processing at higher order stages [80]. Latency is a measure of how fast information is processed at the brain level [71], and the lack of differences in latency between the three study groups may suggest that the speed of access to working memory is similar, whether the subject has a VI or not [34].

4.3. Brain activation patterns

The distinct brain activation patterns revealed by the EEG of the research groups show that tactile information is processed in different regions in EVI, LVI, and CG subjects. This observation is consistent with previous studies [31,81–83]. Specifically, in our study, CG and EVI subjects exhibited higher activity in the frontal areas associated with working memory and attention processes [84]. For example, the left superior and middle frontal regions are thought to be involved in the working memory network and attention [85,86].

In the scientific literature, a close relationship between attention and working memory is generally accepted. Different approaches to this relationship have been proposed [see Oberauer [87] for a comprehensive review]. Broadly speaking, attention helps us orient and focus on a particular aspect, while working memory allows the retention of transient information to carry out the current task [88,89]. These processes are essential for decision-making and problem-solving [89]. Therefore, the increased activity in the frontal areas of our participants may reflect the neural correlates of attention and working memory processes necessary for the execution of the paradigm proposed in the present study. The participants were asked to provide a motor response (press the button) only when horizontal lines appeared [31]; therefore, they had to be actively engaged in this detection task [29] and decide when it was appropriate to press the button.

Remarkably, the neural substrates of working memory involve not only the frontal areas but also other brain regions. One such area is the parietal cortex [86], which was a region of maximum activity in EVI of the present research. The activity of this region in individuals with early-onset VI has also been found in previous studies [90,91]. The parietal lobe is a complex structure associated with the dorsal visual stream, also known as the "where" stream. This pathway is involved in recognizing the spatial characteristics of objects [92] and is believed to be active in individuals with early-onset VI during the recognition of tactile stimuli [93,94]. In addition, the parietal region is thought to be involved in multi-modal processing [95]. This brain region is not only responsible for processing somatosensory information but is also involved in the association of visual, auditory, and somatosensory information [96,97]. Parietal structures have also been linked to several cognitive functions, including language, bottom-up and top-down attention, and working memory [98,99]. Therefore, the greater parietal activity in EVI participants could be due to the fact that these individuals have a greater need for neuronal resources to process information due to the lack of vision from an early age [31]. These compensatory mechanisms may also be associated with neural plasticity during critical developmental periods [100,101], as the absence of visual input in EVI participants might strengthen the neural connections in the somatosensory areas of the parietal cortex [102–104].

Furthermore, the localization results of the brain sources of LVI participants in our study show that these individuals have increased activity in the bilateral superior temporal regions. Previous research has found activation in temporal structures in people with sight loss [31, 103,105]. Notably, Voss et al. [106] found greater activation in the ventral visual pathway in individuals with late-onset VI. The ventral visual pathway, also known as the "what" pathway, is a stream that reaches temporal regions [107] and is responsible for visual object recognition [108]. In conjunction with the above, the superior temporal cortex is involved in spatial recognition and exploration [109], and it serves as a link between the dorsal and ventral pathways in visual processing, facilitating the examination of both object-specific and spatial information [109,110]. Hence, the temporal activity in the LVI individuals may be attributed to compensatory changes for processing non-visual stimuli [111], and an attempt to identify the stimulus that was being projected onto the stimulation matrix. Moreover, the reorganization of activity towards temporal cortical areas in individuals with LVI may reflect compensatory mechanisms that involve visual memory prior to vision loss. This is plausible because the temporal cortex has strong connections with the hippocampus, which is also capable of processing visual information [112]. Studies conducted on individuals without VI have shown temporal cortical activity associated with visual memory encoding [113,114]. Overall, these findings enable us to expand our knowledge of the compensatory brain strategies employed by the VI population, which has often been overshadowed by research that primarily focuses on the reorganization of brain activity in the occipital regions [20,22,103,115].

4.4. Limitations

Finally, one of the limitations of this study lies in the difficulty of generalizing the data due to the specific characteristics of our sample. The inclusion and exclusion criteria of our study required that the participants with VI have particular visual and vision loss acquisition characteristics. Moreover, although the age range inclusion criteria were proposed to reduce variability in P300 latency due to the aging process [29], further research is needed to confirm whether our findings are

applicable to individuals across different age groups. Therefore, our results should be interpreted considering these limitations. In addition, while the obtained sample size aligns with the calculated sample size, future studies should include more participants to enhance the robustness of the findings obtained in this study.

5. Conclusions

The results of the present study indicate that participants with VI exhibit superior performance in recognizing tactile stimuli, as evidenced by their shorter reaction times compared to CG. This enhanced performance appears to stem not from faster cognitive processing but rather from their greater daily experience with tactile detection.

Conversely, both CG and EVI participants showed increased bioelectrical activity in the frontal regions associated with attention and working memory. Additionally, EVI participants exhibited heightened activity in the bilateral parietal regions, which function as multimodal processing stations. This increased parietal activity likely helps individuals with early-onset VI process more information due to their early vision loss. Furthermore, the activation of parietal structures in participants with early-onset VI may be linked to the dorsal stream, which focuses on spatial analysis ("where" the object is). By contrast, participants with late-onset VI show increased activity in the temporal regions associated with the detection of non-visual stimuli and object identification ("what" the object is).

CRediT authorship contribution statement

Mónica Ahulló: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. **M.Luz Sánchez-Sánchez:** Conceptualization, Formal analysis, Writing – review & editing. **Elena Ortiz-Teran:** Formal analysis, Writing – review & editing. **Tomás Ortiz:** Investigation, Supervision, Writing – review & editing. **Enrique Varela-Donoso:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Writing – review & editing.

Ethics declarations

The present study was reviewed and approved by the Institutional Review Board of the San Carlos University Hospital Ethics Committee in Madrid, Spain (approval number: 20/071-E_Tesis, dated March 18, 2020). All procedures performed in this trial conformed to the ethical standards and were conducted in accordance with the Declaration of Helsinki. All participants were informed about the purpose of the investigation and provided written informed consent to participate in the study. The confidentiality and anonymity of the participants were guaranteed at all times throughout the study.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The data is available in a public repository: https://doi.org/10.7910/DVN/KKEJZF

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