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Comparison of temporal judgments in sighted and visually impaired children

Tiziana Battistin[a,*,1], Giovanna Mioni[b,1], Vittorina Schoch[a], Patrizia Silvia Bisiacchi[b,c]

[a] Robert Hollman Foundation, Padova, Italy
[b] Department of General Psychology, University of Padova, Italy
[c] Padova Neuroscience Center, Italy

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ABSTRACT

Aim: We studied visually impaired and blind children to investigate the effects of visual damage on time perception.
Methods: Sixty-three children (11 blind, 16 visually impaired, 20 sighted and 16 sighted but blindfolded) performed a temporal bisection task, which consisted of judging different temporal intervals presented in the auditory modality.
Results: The visually impaired children showed lower constant error than sighted children but higher variability (Weber ratio). The blindfolded children had a temporal estimation comparable to the clinical groups and time sensitivity comparable to the controls.
Conclusion: These findings are interpreted in the light of inter-modality interference, assuming that the coexistence of both sensory modalities, present only in controls, leads to a trade-off between the two senses with an indirect contribution of sight, which does not happen either in the clinical groups or in the blindfolded children, despite the single sensory task.

What this paper adds?

In literature there is a wide range of research on time perception because it is one of the most pervasive and crucial aspects of our mental functioning, being an ubiquitous dimension involved in all motor, perceptual and cognitive activities. Despite its importance in daily life, to our knowledge, there are very few findings on time perception in visually impaired/blind children. The clinical relevance of this research lies in the fact that it studies how visually impaired and blind children perceive temporal stimuli, indicating thus their ability to judge millisecond time durations. We used an auditory temporal bisection task and we compared their responses with those of sighted and blindfolded children.

Our results showed that visually impaired children had a better accuracy (lower constant error) than sighted children, but their performance was more variable (higher Weber ratio). Blindfolded children, who indeed underwent transient "visual deprivation", did not differ from clinical groups in temporal estimation. These results suggest that, in temporal processing, single sensory modality reduced the subjective judgement of overestimation, compared to the coexistence of senses as demonstrated in clinical groups and in blindfolded sighted participants.

These findings are important because they add knowledge of the role of different sensory modalities on temporal abilities; they also help professionals support more appropriately the growth of blind/visually impaired children. Understanding how these children

* Corresponding author at: Robert Hollman Foundation, Via Siena, 1, 35143, Padova, Italy.
E-mail address: t.battistin@fondazioneroberthollman.it (T. Battistin).
[1] Authors contributed equally to the work.

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estimate short time durations is of great importance, because time perception is relevant in many events and behaviours of daily life, such as motor coordination, sport performance or dance/music execution.

1. Introduction

Time frames most of our actions and everyday activities. Walking and talking, for example, rely on time processing in the millisecond to a few seconds range. Even simple movements, perception or cognitive processes, as well as complex behaviour, require an accurate time perception to be well accomplished (Buhusi & Meck, 2005). Unlike vision and audition, there are no dedicated sensors for measuring time (Matthews & Meck, 2016) and the representation of temporal information in the brain, even now, remains one of the most elusive concepts for neuroscientists. Traditionally, processing duration in the second-millisecond range has been explained by the pacemaker-accumulator model (Gibbon, Church, & Meck, 1984), which has been further elaborated by Block and Zakay (1996, 2006) in order to explain the influence of attentional resources on temporal processing.

Some behavioural studies have indicated that the ability to process time depends on sensory input (Grondin, 2003, 2014). Several studies investigated the sensory modality effect on time perception both in adults (Grondin, 2003; Grondin, Roussel, Gamache, Roy, & Ouellet, 2005) and in children (Droit-Volet, Tourret, & Wearden, 2004; Droit-Volet, Meck, & Penney, 2007; Zélanti & Droit-Volet, 2012), demonstrating that temporal intervals are perceived as lasting longer when stimuli are auditory rather than visual and sensitivity to time is better (i.e. lower Weber ratio – WR) in the auditory rather than in the visual modality.

We decided to study temporal perception in blind/visually impaired children, who must rely only on auditory sense, because we were interested in knowing how the total/partial absence of sight influences time estimation. Sight, being a complex dynamic psychological/neurobiological process, is in fact a key area for early child development, belonging to the developing systems for cognition, action and attention (Atkinson, 2017).

1.1. Visual impairment and temporal perception

Visual impairment (VI), which can be congenital or acquired (Bergwerk, 2011), has a severe impact on overall child development. Its perceptual consequences have been explored more extensively in blind/VI adults' auditory and tactile performances focusing on the spatial domain (Bottini, Crepaldi, Casasanto, Crollen, & Collignon, 2015; Cappagli, Cocchi, & Gori, 2017; Finocchietti, Cappagli, & Gori, 2015; Gori, Cappagli, Baud-Bovy, & Finocchietti, 2017), while less research has been directed to address the question of how visual impairment affects temporal perception, especially in children.

Previous studies investigated temporal aspects in blind adults with tactile, audio-tactile and auditory stimuli. Temporal order judgement (TOJ) paradigm is one of the experimental designs used to investigate temporal perception in humans, where participants are presented with pairs of stimuli at various different stimulus onset asynchronies and where they have to judge which stimulus appeared first (Hirsch, 1959). Roder, Rosler, and Spence (2004) provided the first empirical evidence for superior TOJs for tactile stimuli in congenitally blind adults, compared to late blind and sighted adults, suggesting a critical role of childhood vision in modulating the perception of touch, possibly due to the emergence of specific cross-modal links during development. Recently, their results have been also replicated by Crollen, Spruyt, Mahau, Bottini, and Collignon (2019).

Occelli, Spence, and Zampini (2008) studied the potential modulatory effect of relative spatial position on audio-tactile TOJs, in sighted, early and late blind adults. Their results showed that the temporal performance of blind adults was more accurate when the auditory and tactile stimuli were presented from different positions rather than from the same position. The modulation of their performance by the relative spatial position of the stimuli supports the hypothesis that the absence of visual cues results in the emergence of more pronounced audio-tactile spatial interactions. Stevens and Weaver (2005) used an auditory TOJ task in early blind, sighted and blindfolded adults, showing that early blind adults were more sensitive (lower TOJ threshold) than the other two groups, supporting therefore the hypothesis by Neville and Bavelier (2001) that faster temporal processing underlies many auditory compensatory effects in the blind.

Temporal perception in blind adults has also been investigated using another experimental task, which is duration bisection . In this task, participants first learn two standard intervals (short and long) and then are presented with new temporal intervals. Their task is to judge if the new intervals are similar to the standard short or to the standard long previously learned (Penney & Cheng, 2018; Kopec & Brody, 2010). Gori, Sandini, Martinoli, and Burr (2014) reported no significant differences between congenitally blind adults and controls in an auditory temporal bisection task, where three stimuli were presented successively: the first and the last were 75 ms long, while the second stimulus was of a different duration and the two intervals between sounds were 500 ms each. The subjects verbally reported whether the middle sound was temporally closer to the first or to the last. Their results have been replicated by Campus, Sandini, Amadeo, and Gori (2019) more recently.

Finally, Poggel, Treutwein, and Strasburger (2011) and Poggel, Treutwein, Sabel, and Strasburger (2015) investigated whether vision restoration training (VRT), a training programme designed to improve light detection performance, would improve temporal processing in adult patients with partial vision loss after visual pathway lesions. They demonstrated that the training resulted in an improvement of temporal-resolution thresholds, i.e. in a function not specifically trained during treatment, which shows a connection between visual and temporal functions.

There is much less literature on the effect of visual deprivation, especially congenital, on temporal abilities in children: Vercillo, Burr, and Gori (2016) showed no significant differences between sighted and congenitally blind children (9–14 years old), using a temporal bisection task. Children were positioned in front of a single speaker and listened to a sequence of three sounds, and reported whether the second stimulus appeared temporally closer to the first or to the third sound, which were 500 Hz tones of 75 ms duration

at 60 dB. The total duration of the stimulation was 1000 ms. The timing of the second stimulus was variable. This task was done as a control task, because the article focused on the auditory sense of space, showing that auditory deficits in the blind are specific to spatial localization, confirming that audition is more precise than vision in temporal judgements (Gori, Sandini, & Burr, 2012), and is not affected by lack of vision.

Taken together, the previous studies conducted with adults led to mixed and contrasting results, indicating that temporal perception in blind people is still a matter of debate. Moreover, studies on children are still too few and more effort needs to be spent in understanding how visual deprivation affects temporal abilities during developmental age.

1.2. The present study

To our knowledge, this is one of the first studies aimed at studying the relationship between deprivation of sight, either congenital or transitory, and temporal abilities in children during development, addressing the following question: *Do blind/visually impaired children perceive time in the same way as their sighted peers?* The novelty of this study is that we focused on temporal blind/VI children abilities on auditory perception in a younger range of age (6–11 years old) than Vercillo et al. (2016) and that we performed the same task also on a group of blindfolded children, who experienced only a transitory visual deprivation. This procedure allows us not only to check the role of sight deprivation on temporal abilities, but also to highlight the eventual differences between congenital and transient sensory deprivation.

We expected a better performance in blind/visually impaired children, because data from several studies highlights that visual deprivation correlates to improved auditory abilities. This correlation is due to plastic reorganisation (Elbert et al., 2002; Klinge, Eippert, Roder, & Buchel, 2010), both intra-modal plasticity in the auditory cortex (Stevens & Weaver, 2009) and visual–auditory cross-modal plasticity in the right occipital association areas (Weeks et al., 2000).

2. Methods

2.1. Participants

Sixty-three participants were included in the study. Eleven children were blind (mean age M = 8.82 years, *SD* = 1.78; male = 6), 16 were visually impaired (M = 8.00 years, *SD* = 1.60; male = 13), 20 were sighted (M = 9.05 years, *SD* = 1.19; male = 7). In addition we added a group of 16 sighted children, who performed the time task completely blindfolded (M = 9.31 years, *SD* = 1.14; male = 10), so with no chance at all of using sight.

The visual deficit was assessed under the ICD-10 (World Health Organization (WHO, 2016), according to which moderate visual impairment (category 1) is related to visual acuity 0.1–0.3; severe visual impairment (category 2) is related to visual acuity 0.05–0.1; complete blindness (category 3–5) is related to visual acuity 0.05 to light perception.

The majority of children (10 out of 11 blind children and 13 out of 16 visually impaired children) had been totally/partially deprived of sight from birth (congenital visual impairment).

All children's parents gave their informed consent to include their children in the study and all participants were informed that participation was voluntary and that they could interrupt the testing section at any time. The study was approved by the local Ethics Committee and was carried out in agreement with the Helsinki Declaration (59th WMA General Assembly, Seoul, 2008).

We did not include visually impaired children with cerebral visual impairment, or with other disabilities (sensory, motor or cognitive), so all the visually impaired children were characterised by peripheral eye damage.

Table 1 summarises the characteristics and the clinical features of the sample.

No differences in terms of age [$p = .070$, $\eta_p^2 = 0.12$] were observed between groups.

2.2. Procedure

Blind and visually impaired children were recruited and tested individually at the Robert Hollman Foundation (Padova, Italy), while sighted children were recruited from the local community and they were tested at the Department of General Psychology (University of Padova, Italy) or in their own homes. All participants first performed an auditory temporal bisection task (25 min) (Droit-Volet & Wearden, 2001; Kopec & Brody, 2010; Penney & Cheng, 2018) and subsequently performed two subtests of the Weschler Intelligence Scale for Children-IV (WISC IV, Petermann & Petermann, 2011) to verify/exclude possible differences in their cognitive profiles.

2.2.1. Time bisection task

Participants sat in front of a PC in a quiet room. The time bisection task consisted of a learning phase and a test phase. In the learning phase the participants listened to 10 short (S = 300 ms) and 10 long (L = 900 ms) standard durations: short standard were presented first as often done in previous studies (Kopec & Brody, 2010; Penney & Cheng, 2018). The auditory stimulus was a pink noise, which was synthesized at a sample rate of 44.1 kHz and a 16-bit resolution and was generated by an M-AUDIO Fast Track Pro soundcard. The output of the soundcard was passed binaurally through a pair of circumaural, closed-back, sound-isolating Sennheiser HD 280 pro headphones, at a level of 65 dB SPL. Both standard durations were presented 10 times in the learning phase, so that the children could memorize them. After the learning phase, a test phase was performed, in which 7 comparison durations, between the two standards, were used: 300, 400, 500, 600, 700, 800 and 900 ms. Participants were required to judge the durations of new

Table 1
Demographic and clinical characteristics of blind and visually impaired children.

Sex	Age	Pathology	Onset	Visual Impairment	Category VI
M	10	Leber's Amaurosis	Congenital	Blindness H54.0	4
F	6	Leber's Amaurosis	Congenital	Blindness H54.0	5
F	9	Retinal dystrophy	Congenital	Blindness H54.0	4
M	8	Bilateral Glaucoma	Congenital	Blindness H54.0	5
M	10	Bilateral Glaucoma	Congenital	Blindness H54.0	5
F	7	Retinopathy of premature with retinal detachment	Congenital	Blindness H54.0	5
M	6	Retinopathy of premature with retinal detachment	Congenital	Blindness H54.0	5
F	7	Retinopathy of premature	Congenital	Blindness H54.0	4
M	11	Retinopathy of premature	Congenital	Blindness H54.0	5
F	10	Microphthalmia with retinal alterations	Congenital	Blindness H54.0	5
M	11	Glioma of optical paths with optic nerves' atrophy	Acquired (3 months)	Blindness H54.0	4
M(SD)	8.82 (1.78)	–			
M	6	Retinal dystrophy in Alstrom Sdr.	Congenital	VI H54.1	2
M	6	Retinal dystrophy	Congenital	VI H54.2	1
M	8	Retinal dystrophy	Congenital	VI H54.2	1
M	10	Tapeto-retinal degeneration	Congenital	VI H54.2	1
F	7	Bilateral Glaucoma	Congenital	VI H54.4	2
M	6	Retinopathy of premature	Congenital	VI H54.2	1
M	6	Microphthalmia with retinal alterations	Congenital	VI H54.1	2
M	7	Glioma of optical paths with optic nerves' atrophy	Acquired (4 yrs)	VI H54.5	1
M	8	Glioma of optical paths with optic nerves' atrophy	Acquired (1 yr 2 mo)	VI H54.4	2
M	6	Glioma of optical paths with optic nerves' atrophy	Acquired (1 yr 6 mo)	VI H54.4	2
F	10	Cataract	Congenital	VI H54.2	1
F	6	Achromatopsia	Congenital	VI H54.1	2
M	9	Achromatopsia	Congenital	VI H54.1	2
M	6	Achromatopsia	Congenital	VI H54.1	2
M	11	Achromatopsia	Congenital	VI H54.1	2
M	9	High myopia and subluxation of crystalline lens	Congenital	VI H54.2	1
M(SD)	8.00 (1.60)	–			

Visual Impairment (VI) is classified according to ICD10 (2016).

intervals and determine if they were closer in duration to the 'short standard' or to the 'long standard'. Responses were given pressing, according to the judgement, one of two keys on the PC keyboard with right or left index fingers. The two keys had been covered with a tactile label (smooth vs. rough). Response keys were counterbalanced between participants. After the response, there was a 1000 ms inter-trial interval. There was no feedback for correct or incorrect responses. The task was divided into 4 blocks and in each block each duration (300-400-500-600-700-800-900 ms) was presented 7 times for a total of 49 trials.

2.2.2. Neuropsychological tests

To characterise the sample also on a cognitive profile, children performed two subtests of the WISC-IV (Petermann & Petermann, 2011): the digit span (forward and backward) and the vocabulary subtests. In the forward digit span test, the experimenter read out a sequence of numbers and the participant had to repeat it, respecting the same order, assessing short-term memory (STM). In the backward digit span, the participant had to repeat the sequence of numbers in reverse order, checking, therefore, working memory (WM) skills. The vocabulary subtest was used to check vocabulary ability, word knowledge and word usage, verbal fluency and concept formation. A list of words was presented and participants had to explain the meaning of every word. Scores were calculating summing the exact responses and then raw scores were converted in weighed scored according to data of reference for age.

Table 2 presents the mean weighted scores in each group in the neuropsychological tests, according to data of reference for age. No differences in terms of either STM [p = .097, η_p^2 = 0.10; blind children mean = 6.45 (1.12); visually impaired children

Table 2
Neuropsychological mean weighted scores of the four groups.

Children Group	Digit Span Forward M (SD)	Digit Span Backward M (SD)	Vocabulary M (SD)
Blind	6.45 (1.12)	3.63 (2.11)	12.18 (3.22)
Partially Visual Loss	5.31 (1.49)	3.12 (1.25)	13.75 (3.04)
Sighted	5.90 (0.94)	3.40 (1.18)	13.30 (2.43)
Blindfolded	6.00 (1.09)	4.31 (0.95)	12.31 (2.06)

Note: Two Wisc IV subtests were performed: Digit span subtest and Vocabulary subtest. In the Digit Span subtest participants were required to repeat a sequence of number either in the correct (Forward) and reverse (Backward) order. In the Vocabulary subtest, a list of words was presented and participants had to explain the meaning of every word. Scores were calculating summing the exact responses and then raw scores were converted in weighed scored according to data of reference for age.

Table 3
Descriptive statistic for Bisection Points (BP), Constant Errors (CE) and Weber Ratio (WR) as a function of Group.

	Blind children M (*SD*)	Visually impaired children M (*SD*)	Sighted children M (*SD*)	Blindfolded children M (*SD*)
BP	550 (35)	574 (61)	501 (46)	552 (42)
CE	50 (35)	26 (61)	98 (46)	48 (42)
WR	0.38 (0.24)	0.31 (0.11)	0.22 (0.13)	0.23 (0.06)

Note: BP = Bisection Point; CE = Constant Error; WR = Weber Ratio; M = mean; SD = standard deviation.

mean = 5.31 (1.49); sighted children mean 5.90 (0.94) and blindfolded children mean = 6.00 (1.09)] or WM [$p = .089$, $\eta_p^2 = 0.10$; blind children mean = 3.63 (2.11); visually impaired children mean = 3.12 (1.25); sighted children mean 3.40 (1.18) and blindfolded children mean = 4.31 (0.95)] were observed between groups. No differences between groups were observed also in the Vocabulary subtest [$p = .315$, $\eta_p^2 = 0.06$; blind children mean = 12.18 (3.22); visually impaired children mean = 13.75 (3.04); sighted children mean = 13.30 (2.43) and blindfolded children mean = 12.31 (2.06)].

2.3. Data analyses on time bisection task

For each participant a seven-point psychometric function was traced, plotting the seven comparison intervals on the *x*-axis and the probability of responding 'long' (p long) on the y-axis. The cumulative normal function was fitted to the resulting curves. The mean value of goodness-of-fit for each group was highly acceptable, with blind R2 = 0.91, visually impaired R2 = 0.88, sighted R2 = 0.97 and blindfolded children R2 = 0.98 respectively.

Temporal abilities were first analysed in terms of the proportion of long responses (raw data), and then in terms of Constant Error (CE) and Weber Ratio (WR). The CE is defined as the duration of the mid-point between both standards (300 and 900 ms) minus the Bisection Point (BP) (Grondin, Laflamme, Bienvenue, Labonté, & Roy, 2015) and it is a measure of accuracy, positively related to perceived duration. Positive or negative CE values are an index of over- or under-estimation of temporal durations compared to the mid-point. The BP is the stimulus duration to which the participants responded "short" or "long" with equal frequency. It is defined as the target duration corresponding to a predicted rate of *long* responses of 50%, and it is used as a measure of perceived duration: the smaller the BP value, the longer the perceived duration. The mean BP values, reported on Table 3, are also given here for better comparison with previous studies (Droit-Volet & Wearden, 2001; Zélanti & Droit-Volet, 2012).

WR is defined as the standard deviation parameter of the fitted cumulative curve divided by the actual mid-point between both standards. This variable measures the participants' sensitivity to time; higher WR values denote poorer sensitivity.

Analyses of variance (ANOVA) were conducted on the proportion of long responses with *Group* as a between-subjects factor (blind, visually impaired, sighted and blindfolded children) and *Temporal interval* as a within-subjects factor (300, 400, 500, 600, 700, 800, and 900 ms).

Moreover, in order to further investigate the contribution of age, working memory and language on temporal judgement, clinical population analyses of covariance (ANCOVA) were conducted on CE and on WR with *Group* (blind, visually impaired, sighted and blindfolded children) as a between-subjects factor; age, working memory and vocabulary were used as covariates.

The significant analyses were followed by post-hoc analyses with Bonferroni's correction to reduce the Type I error rate, and the effect size was estimated with the partial eta squared index (η_p^2).

3. Results

Fig. 1 shows the proportion of long responses plotted against comparison durations for all the groups of children. The data analysed in terms of the proportion of 'long' responses showed a main effect of *Group* [$F(1,59) = 7.35$, $p < .001$, $\eta_p^2 = 0.27$], indicating that sighted children differed from the other groups by pressing 'long' more times. Moreover, a significant main effect of temporal interval [$F(6,336) = 2.56$, $p = .020$, $\eta_p^2 = 0.04$] was shown, indicating that participants pressed 'long' more times as the duration of the comparison temporal intervals increased, in line with previous studies conducted with sighted children (Droit-Volet, 2013; Droit-Volet & Wearden, 2001; Droit-Volet & Zelanti, 2013).

A significant interaction Temporal interval × Group [$F(6,354) = 3.12$, $p < .001$, $\eta_p^2 = 0.14$] was found. Generally, all children increased the proportion of 'long' responses as the temporal interval increased (all $ps = .001$, all $\eta_p^2 \geq 0.89$). Importantly, significant differences between groups emerged as standard duration increased; specifically, sighted children pressed "long" more times than visually impaired children from 500 ms and longer (all $p \leq .05$; all $\eta_p^2 \geq 0.15$) and they pressed "long" more times than blind children at 600, 800 and 900 ms (all $p \leq .05$; all $\eta_p^2 = 0.18$).

The data analysed in terms of CE showed a main *Group* effect [$F(3,56) = 7.17$, $p < .001$, $\eta_p^2 = 0.28$] (Fig. 2); post hoc analyses indicated that sighted children over-estimated time more than all other groups while blind, visually impaired and blindfolded children performed the task equally. No contribution of age, working memory or vocabulary was found (all $ps \geq .184$, $\eta_p^2 \leq 0.03$).

The data analysed in terms of WR showed a main effect of *Group* [$F(3,56) = 4.41$, $p = .007$, $\eta_p^2 = 0.19$], indicating that blind and visually impaired children were more variable than sighted and blindfolded children (Fig. 3).

Moreover, a main effect of working memory [$F(1,56) = 22.99$, $p < .001$, $\eta_p^2 = 0.29$] was also found. No contribution of age or

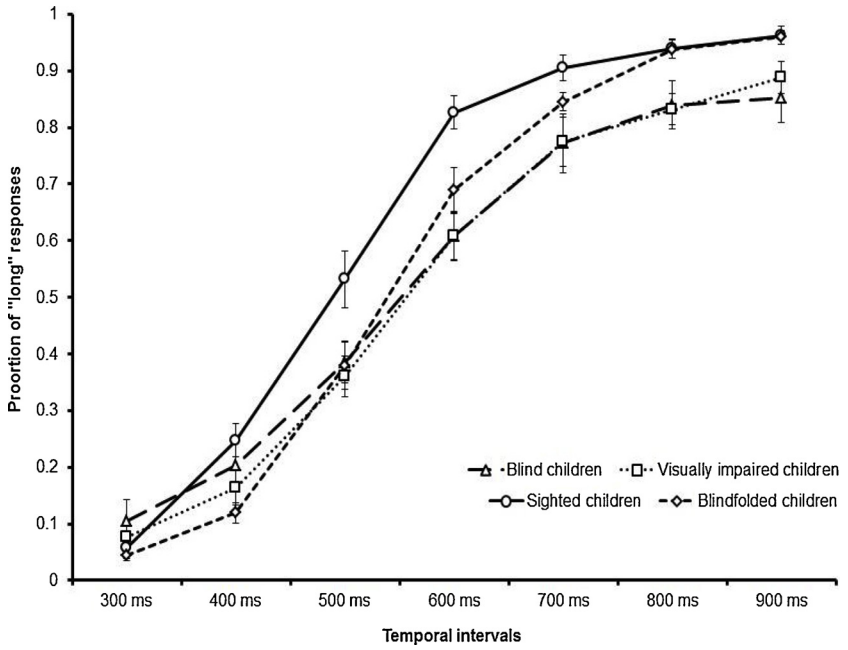

Fig. 1. Proportion of long responses as a function of groups and temporal intervals. Error bars indicate ± standard errors.

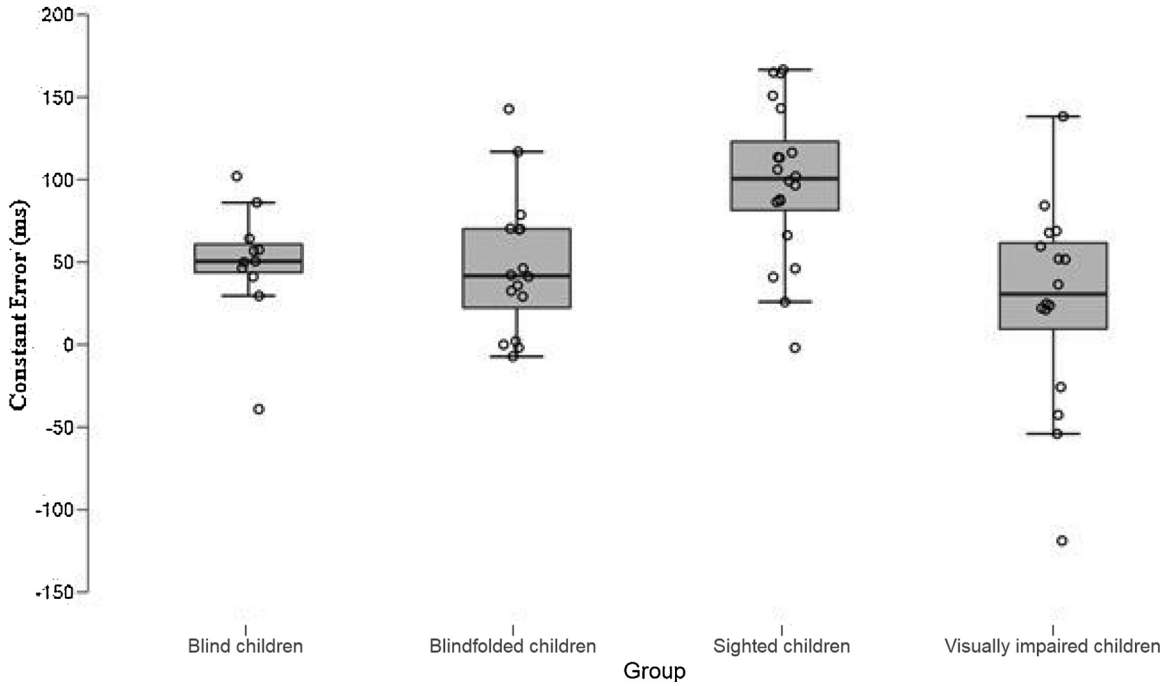

Fig. 2. Constant Error (CE) as a function of Group. Each dot represents a participant.

vocabulary was found (all $p \geq .156$, $\eta_p^2 \leq 0.04$).

4. Discussion

The main goal of the present research was to investigate how the total or partial absence of sight affects time estimation. We expected a difference between clinical and non-clinical groups, with blind and visually impaired children showing greater accuracy (lower CE) and higher temporal sensitivity (lower WR) than sighted children in the auditory modality, because data from several studies highlights that visual deprivation correlates to improved auditory abilities (Elbert et al., 2002; Klinge et al., 2010; Stevens &

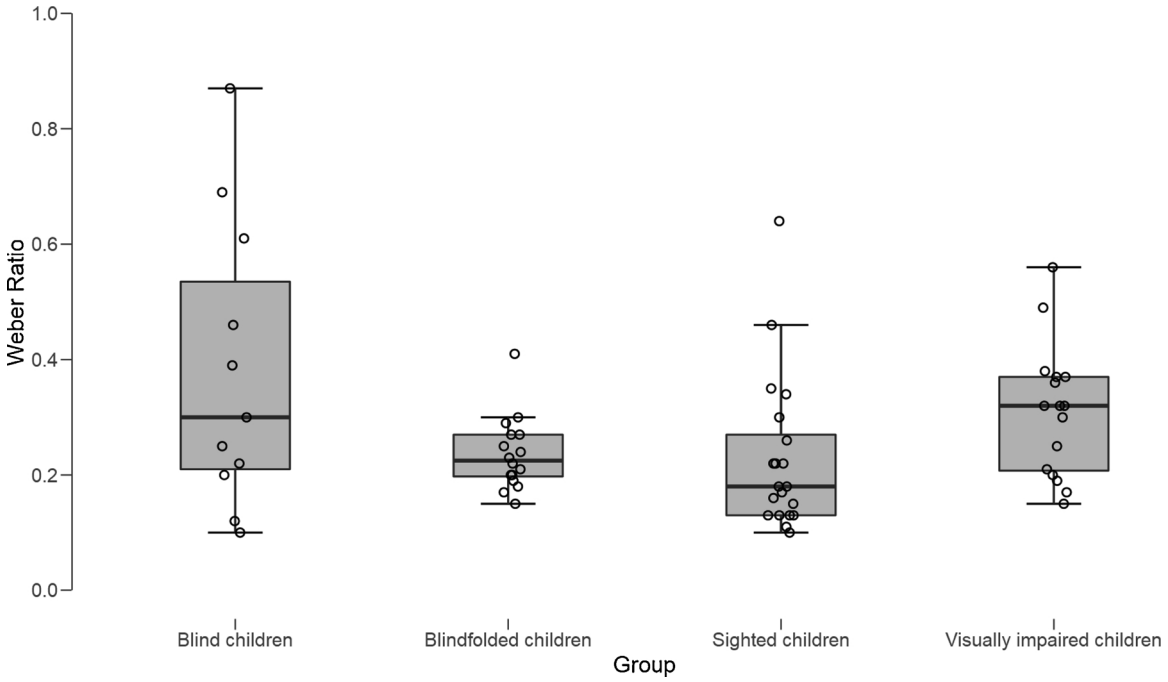

Fig. 3. Weber Ratio (WR) as a function of Group. Each dot represents a participant.

Weaver, 2009; Weeks et al., 2000). Results partially confirmed our hypothesis.

Analyses conducted on the proportion of long responses (Fig. 1) showed a main effect of group, indicating a greater tendency in sighted children to respond "long" more than the other three groups. This bias towards responding "long" in sighted children is supported by data on CE, which is a measure of accuracy. We found a main group effect indicating lower temporal abilities in sighted children compared to the other groups. Taking together such findings supports the idea that timing decisions are more accurate when a single sensory modality is involved. A higher WR, which gives a measure of the steepness of the psychophysical function (Droit-Volet & Wearden, 2001), was found in clinical groups and thus indicates a greater variability which may be due to the presence of individual differences, as described by Matthews and Meck (2014) in their review and which can be intensified in clinical populations like ours (Greenaway & Dale, 2017).

The majority of studies investigating temporal abilities in children (Droit-Volet, 2011, 2013) has revealed that children's sensitivity to time improves with age. When the durations are easy to discriminate (ratio of 1:4 or 1:2), and when the temporal range under investigation is shorter than 1 s the slope of the psychometric functions in bisection tasks always increases with age (Droit-Volet & Wearden, 2001). Children aged 3 and 5 years systematically produce flatter psychometric functions than older children. At the age of 8 years, the slope of the bisection curve becomes closer to that produced by adults (Zélanti & Droit-Volet, 2012). Droit-Volet (2011) discussed that the development of attention-related cognitive capacities, as well as that of the executive functions, which depend upon the slow maturation of the frontal cortex, explain in great part developmental changes in the ability to discriminate time and the reduction in temporal sensitivity (WR).

Our results showed indeed, no effect of age, WM and vocabulary on proportion of long responses and CE, while we observed a main effect of WM on WR. Looking at the individual data, we also observed greater variability of response in the clinical groups, but not in the blindfolded and control groups, suggesting that variability is intrinsically more connected to the difficulty in maintaining a stable temporal representation in memory than to the temporal task. This greater variability has been observed elsewhere in other clinical populations (Cester, Mioni, & Cornoldi, 2017; Mioni, Mattalia, & Stablum, 2013; Mioni, Santon, Stablum, & Cornoldi, 2017). Moreover, the main effect of WM on WR confirms that working memory affects temporal sensitivity (Droit-Volet & Wearden, 2001; Matthews & Meck, 2016), independently of the group. Children with lower WM behaved differently from the others independently of the group to which they belonged. These results were confirmed also by the separate analysis on digit span forward and digit span backward, which showed no differences between groups. This finding is partially different from previous studies on STM and WM in blind versus sighted children, where blind children outperformed their sighted peers on both STM and WM tasks (Whitagen, Kappers, Vervloed, Knoors, & Verhoeven, 2013), but their mean age (M = 10.71; SD = 2.01) was higher than the age of our blind group (M = 8.82; SD = 1.78) and it is known that WM abilities increase with age (Camos & Barrouillet, 2011) since there is an improvement in executive functions probably due to the maturation of frontal lobes.

Another interesting finding emerged from the blindfolded group: although all four groups of children underwent an auditory temporal bisection task, blindfolded children showed temporal abilities (lower CE) statistically different from the sighted children and comparable to the clinical groups, while their temporal sensitivity was not statistically different from sighted children.

From their behaviour it seems that in temporal processing a crucial role is played not only by the physical modality of the

stimulus, but also by the concurrence/combination of different sensory components in performing the auditory task. According to our data, the use of single sensory modality reduced the bias towards responding long, compared to the presence of multisensory components.

FMRI studies have also been conducted to evaluate functional reorganization of visual areas in clinical populations. Guerreiro, Putzar, and Roder (2015) demonstrated that adults who underwent transient visual deprivation in early life because of a congenital cataract, did not exhibit multisensory integration in auditory areas unlike sighted controls. Their results showed a visual cortical processing within the visual cortex, which was lower during audio-visual stimulation than during only visual stimulation. This suggests not only that the lack of vision in critical periods of early life leads to a reorganisation of the visual cortex, but also that congenital visual deprivation affects the ability of cortical areas to integrate cross-modal inputs, possibly because visual processing is suppressed during cross-modal stimulation (Guerreiro et al., 2015). An additional fMRI study conducted by Collignon et al. (2013) showed the impact of blindness onset on the functional organization and the connectivity of the occipital cortex, demonstrating how a congenital visual deprivation modifies the architecture of occipital circuits in a fundamental way.

At the same time, the findings in the blindfolded group seem to support the use of a single modality for better accuracy, independently of brain plasticity and reorganisation in blind people (Klinge et al., 2010; Weeks et al., 2000), but more detailed studies, focusing also on attentional components, are needed.

In conclusion, our results may be interpreted mainly according to the hypothesis of inter-modality interference, assuming that, in controls, the simultaneous presence of sight and audition leads to a trade-off between the two senses, which are not present in the clinical groups, nor in the blindfolded one. Sight therefore seems to contribute to temporal perception also in an auditory task (and probably viceversa), confirming the connection between vision and temporal abilities.

Limitations of this study are primarily due to the small sample size, especially blind children, and to the range of ages (6–11 years old) considered. In particular, age is a critical factor to take into account in our study, considering the age-related modification in high cognitive abilities that occurs between 6 and 11 years old (Zélanti & Droit-Volet, 2012). Despite the fact that no main effect of age on WR was shown in this study, it does not mean that age is not affecting it at all, because it could be due to the characteristics of our clinical sample. The overall development of blind/visually impaired children is more difficult and articulate, because it must rely on other senses; sensory processing is strictly related to sensory characteristics and vision is the only sense which has an analytical and comprehensive perception at the same time. The loss of this sense means that times for learning are dilated, especially in the first years of life, needing the constant and essential help of parents/caregivers in the interaction with an adequate environment (Brambring, 2004; Fraiberg, 1977; Greenaway & Dale, 2017).

The present research should be considered as a preliminary study to test time perception in visually impaired/blind children. Extensive studies with a larger sample need to be conducted to confirm our data. Nevertheless, these results extend our knowledge of the connection between sensory modalities and time processing during development, but it also has an impact on clinical practice, especially on rehabilitation. Future studies should concentrate on the application of the present results in visually impaired child rehabilitation: a potential field of study might be the link between temporal abilities and motor coordination. In fact, according to the delays also in the motor development (Brambring, 2007; Hallemans, Ortibus, Truijen, & Meire, 2011), it would be interesting to insert timing tasks associated to motor actions, like haptic exploration tasks or walking. A recent study by Cappagli et al. (2019) showed how perceptual development in the case of blindness can be enhanced with naturally associated auditory feedback to body movements; the introduction therefore of a temporal cue in an audio-motor task might be useful to help blind/visually impaired children in coordinating their movement in their surrounding space. The link between temporal cues and space estimations has been in fact also shown (Amadeo, Campus, & Gori, 2019a, 2019b; Gori, Amadeo, & Campus, 2018;), indicating how temporal cues influence space estimations on blind participants and suggesting that blind individuals use temporal information to infer spatial environmental coordinates.

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Declaration of Competing Interest

The authors declare no competing financial interests.

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