



ELSEVIER

Contents lists available at ScienceDirect

Brain and Cognition

journal homepage: www.elsevier.com/locate/b&c

Finding the balance between capture and control: Oculomotor selection in early deaf adults



Benedetta Heimler^{a,*}, Wieske van Zoest^a, Francesca Baruffaldi^a, Mieke Donk^c, Pasquale Rinaldi^d, Maria Cristina Caselli^d, Francesco Pavani^{a,b}

^a Center for Mind Brain Sciences (CIMEC), University of Trento, Italy

^b Department of Psychology and Cognitive Sciences, University of Trento, Italy

^c Department of Cognitive Psychology, VU University Amsterdam, Amsterdam, The Netherlands

^d Institute of Cognitive Sciences and Technologies, National Research Council (ISTC-CNR), Rome, Italy

ARTICLE INFO

Article history:

Accepted 7 March 2015

Keywords:

Early-deafness
Overt visual selection
Stimulus-driven
Goal-driven
Oculomotor capture
Plasticity

ABSTRACT

Previous work investigating the consequence of bilateral deafness on attentional selection suggests that experience-dependent changes in this population may result in increased automatic processing of stimulus-driven visual information (e.g., saliency). However, adaptive behavior also requires observers to prioritize goal-driven information relevant to the task at hand. In order to investigate whether auditory deprivation alters the balance between these two components of attentional selection, we assessed the time-course of overt visual selection in deaf adults. Twenty early-deaf adults and twenty hearing controls performed an oculomotor additional singleton paradigm. Participants made a speeded eye-movement to a unique orientation target, embedded among homogenous non-targets and one additional unique orientation distractor that was more, equally or less salient than the target. Saliency was manipulated through color. For deaf participants proficiency in sign language was assessed. Overall, results showed that fast initiated saccades were saliency-driven, whereas later initiated saccades were goal-driven. However, deaf participants were overall slower than hearing controls at initiating saccades and also less captured by task-irrelevant salient distractors. The delayed oculomotor behavior of deaf adults was not explained by any of the linguistic measures acquired. Importantly, a multinomial model applied to the data revealed a comparable evolution over time of the underlying saliency- and goal-driven processes between the two groups, confirming the crucial role of saccadic latencies in determining the outcome of visual selection performance. The present findings indicate that prioritization of saliency-driven information is not an unavoidable phenomenon in deafness. Possible neural correlates of the documented behavioral effect are also discussed.

© 2015 Elsevier Inc. All rights reserved.

1. Introduction

The most evident and intuitive consequence of bilateral hearing impairment is that deaf adults interact with a silent and primarily visual world. In this atypical sensory condition, visual processing alone needs to fulfill two fundamental functions of attentional selection: (1) the automatic orientation to unexpected and salient visual events in the external environment (i.e., stimulus-driven selection), and (2) the ability to steer visual behaviors in a voluntary goal-driven manner to complete intentional tasks or actions. The majority of studies on visual attention in the early-deaf

population have documented a reorganization occurring in both these fundamental attentional components, albeit typically examining these two attentional functions separately from one another (see [Dye and Bavelier \(2010\)](#) and [Pavani and Röder \(2012\)](#) for reviews). However, everyday life behaviors are most often the outcome of the interaction between these two aspects of visual selection. In the literature on deafness the fundamental question how auditory deprivation alters this interaction has never being directly addressed.

Recent findings in the hearing population demonstrated the crucial role of time in disambiguating the relative contributions to performance of stimulus- and goal-driven behaviors (e.g., [van Zoest, Donk, & Theeuwes, 2004](#); [van Zoest & Donk, 2005, 2008](#)). These studies investigated the temporal dynamics of the interplay between these two attentional selection components by

* Corresponding author at: Center for Mind Brain Sciences (CIMEC), University of Trento, Corso Bettini 31, 38068 Rovereto, Italy. Fax: +39 0464 808602.

E-mail address: Benedetta.Heimler@mail.huji.ac.il (B. Heimler).

manipulating the relative saliency of stimuli presented in search displays, while registering participants' eye-movements. Results show that fast initiated eye-movements following scene onset are predominantly driven by automatic attentional capture to salient stimuli, independently of whether or not these salient elements are relevant for the task. Instead, it takes time for voluntary, intentional strategies to be efficiently implemented in behavior (see [van Zoest, Hunt, and Kingstone \(2010\)](#) for review). The aim of the present study is to investigate the temporal interplay of the relative contribution of stimulus- and goal-driven components of attentional selection in deaf adults, to find out to what extent auditory deprivation modulates this interaction.

The recording of eye-movements furthermore allows us to expand the understanding of *overt* attentional mechanisms in the deaf population. Until now overt attention has received very little consideration beyond research on sign language processing (e.g., [Agrafiotis et al., 2006](#); [Letourneau & Mitchell, 2010](#); [Emmorey, Thompson, & Colvin, 2009](#); [Muir & Richardson, 2005](#)) or reading abilities ([Bélanger & Rayner, 2013](#); [Bélanger, Slattery, Mayberry, & Rayner, 2012](#); [Jensema, Danturthi, & Burch, 2000](#); but see [Bottari, Valsecchi, & Pavani, 2011](#); [Watanabe, Matsuda, Nishioka, & Namatame, 2011](#)). In fact, the majority of studies that examined visual attention and visual selection in the deaf population have focused on covert attention mechanisms (see [Bavelier, Dye, and Hauser \(2006\)](#) for review).

1.1. Reorganization of stimulus-driven control in early bilateral deafness

Research on the effects of stimulus-saliency on attentional selection in early deaf adults have primarily focused on covert spatial orienting using abrupt onsets as visual stimuli. These studies typically show faster and more efficient automatic orienting, particularly for the periphery of the visual field in deaf participants compared to hearing controls (see [Pavani and Bottari \(2012\)](#) for reviews). For instance, it has been repeatedly shown that deaf adults are faster in responding to abrupt visual events compared to hearing controls (e.g., [Bottari, Nava, Ley, & Pavani, 2010](#); [Heimler & Pavani, 2014](#); [Loke & Song, 1991](#)). Deaf adults have also been reported to be faster than hearing controls in reorienting visual attention to the peripheral portion of the visual field in response to abrupt onsets of static ([Chen, Zhang, & Zhou, 2006](#); [Colmenero, Catena, Fuentes, & Ramos, 2004](#); but see [Parasnis & Samar, 1985](#) for similar results with central visual stimuli) as well as of moving visual events ([Bosworth & Dobkins, 2002](#)). Furthermore, an electroencephalography (EEG) study ([Bottari, Caclin, Giard, & Pavani, 2011](#)) documented that the faster detection of visual stimuli in the deaf population positively correlate with the amplitude of the P1, an early component of visual processing peaking around 100–130 ms post-stimulus. This finding led [Bottari, Caclin, et al. \(2011\)](#) to conclude that faster response times to visual stimuli in deaf adults reflects early changes in the temporal dynamic of visual processing (see also [Hauthal, Thorne, Debener, & Sandmann, 2013](#)). Given that abrupt onsets represent a salient stimulus-feature, all the aforementioned results might be interpreted as evidence for enhanced sensitivity in the deaf population for the detection of salient information in the surrounding visual environment and particularly in the periphery of the visual field.

Other findings arising from distractor compatibility tasks further corroborate and extend this interpretation (e.g., [Chen, He, Chen, Jin, & Mo, 2010](#); [Proksch & Bavelier, 2002](#); see also [Dye, Baril, and Bavelier \(2007\)](#) for converging evidence coming from a similar task). These studies consistently demonstrated that the presence of a peripheral visual distractor, incompatible in shape with a concurrent visual target, interferes more with performance

in deaf adults than in hearing controls ([Chen et al., 2010](#); [Proksch & Bavelier, 2002](#); but see [Hauthal, Neumann, & Schweinberger, 2012](#)). Based on similar interpretations of results in the hearing population, this result may be explained as evidence for increased attentional resources devoted to the peripheral visual field in the deaf population ([Lavie, 1995](#); [Lavie & Cox, 1997](#); [Maylor & Lavie, 1998](#)). Notably, this result may also be interpreted as suggesting an increased attentional capture by salient information presented in the visual periphery (i.e., shape incompatible distractor) in deaf adults compared to hearing controls.

Several neuroimaging studies suggest that this increased processing of peripheral, salient visual information in the deaf population may rely on strengthened feed-forward connections between the visual areas and the posterior parietal cortex (PPC; e.g., [Bavelier et al., 2000, 2001](#); [Scott, Karns, Dow, Stevens, & Neville, 2014](#)). Crucially, PPC is considered one of the key regions in which sensory (saliency) and goal-driven information are integrated (e.g., [Jerde, Merriam, Riggall, Hedges, & Curtis, 2012](#)). In fact, this cortical region is directly connected to visual areas, from which it receives sensory-related information, but also to the prefrontal cortex (PFC) and the frontal-eye-field (FEF), from which it receives goal-driven information relevant for the task participants are undertaking (e.g., [Corbetta & Shulman, 2002](#); [Kastner & Ungerleider, 2000](#); see [Ptak, 2012](#) for a review).

1.2. Reorganization of the goal-driven control in early bilateral deafness

A parallel line of work in the last decade has examined voluntary deployment of attention in visual selection processes in the deaf population. This research has also mainly tapped into covert-attention mechanisms, mostly presenting stimuli in the center of the visual field (e.g., [Dye & Bavelier, 2010](#); [Parasnis, Samar, & Berent, 2003](#); [Sladen, Tharpe, Ashmead, & Grantham, 2005](#); [Stivalet, Moreno, Richard, Barraud, & Raphel, 1998](#); for results with peripheral visual stimuli see [Bottari et al., 2008](#)) or presenting them at both central and peripheral locations ([Dye, Hauser, & Bavelier, 2009](#)). For instance, [Parasnis et al. \(2003\)](#) tested a group of deaf adults and a group of hearing controls in a vigilance task on central stimuli (test of variable attention, T.O.V.A.). This test provides a measure of the maintenance of focused attention over time and the impulsivity related to the response. [Parasnis et al. \(2003\)](#) reported reduced perceptual sensitivity in the focused attention task and increased response-impulsivity in deaf participants compared to hearing controls. These results could reflect the difficulty of deaf participants in implementing efficient voluntary behaviors to select task-relevant visual information. Furthermore, they corroborate the notion that auditory-deprivation could change visual selection mechanisms, prioritizing stimulus-driven over goal-driven selection. However, other studies on covert attention in deaf adults have failed to replicate similar performance difficulties when stimuli were presented in the center of the visual field ([Bottari et al., 2008](#); [Dye & Bavelier, 2010](#)) or they have even revealed an advantage in deaf participants compared to hearing controls ([Sladen et al., 2005](#); [Stivalet et al., 1998](#)). For instance, [Stivalet et al. \(1998\)](#) presented a central search task to deaf and hearing adults varying the difficulty of the search. The authors found that deaf adults were faster than hearing controls at correctly identifying a target embedded within multiple distractors, yet this finding was observed only in the most difficult search condition ([Stivalet et al., 1998](#)). The authors suggest that deaf adults implement parallel rather than serial search modes when search is difficult, which can lead to more efficient voluntary attentional deployment in the center of the visual field compared to hearing controls ([Stivalet et al., 1998](#)). Using the Eriksen flanker task with distractors positioned either at foveal or at perifoveal

locations (i.e., maximal eccentricity was 3° of visual angle), Sladen et al. (2005) reported overall slower reaction times as well as overall fewer errors in deaf adults compared to hearing controls. The authors suggest that under certain conditions, deaf adults might be more deliberate than hearing controls in releasing their responses, a strategy that could ultimately reduce capture by salient task-irrelevant visual information (Sladen et al., 2005). However, Bottari et al. (2008) examined search efficiency in a change blindness task for perifoveal as well as for peripheral stimuli in deaf and hearing adults and found comparable responses between the two groups, suggesting that voluntary attention deployment was not affected by early auditory deprivation.

Overall, these results indicate that deaf adults are capable of voluntarily engaging and directing visual selection. Nonetheless, they also highlight that a consensus regarding the properties of voluntary attention in the deaf population is still lacking, especially for the periphery of the visual field. As a consequence of the ambiguous behavioral results, a reliable assessment of the neural mechanisms underlying voluntary attention deployment in the deaf population has proved difficult. In fact, neuroimaging studies have mainly focused on the investigation of the neural changes underlying the more consistent stimulus-driven attentional behavioral modulations observed in the deaf population (e.g., Bottari, Caclin, et al., 2011; Scott et al., 2014; Shiell, Champoux, & Zatorre, 2014; Vachon et al., 2013).

1.3. The interplay between stimulus- and goal-driven mechanisms

To the best of our knowledge, there is one study that attempted to directly investigate the relative contribution of stimulus-driven and voluntary control in the visual selection process of deaf adults. Bottari, Valsecchi, et al. (2011) compared deaf signers and hearing participants in a pro- and anti-saccade task (i.e., an overt selection task). Typically, when making a pro-saccade participants are asked to make a direct eye-movement (saccade) to a target-stimulus appearing in the visual scene, whereas when an anti-saccade is requested, the saccade has to be directed in the opposite direction with respect to the delivered visual stimulus (Everling & Fischer, 1998; Hallett, 1978). In the work by Bottari, Valsecchi, et al. (2011), participants were instructed in each trial whether they would have to produce a pro-saccade or an anti-saccade. Results showed more mistakes in the anti-saccade trials and faster eye-movements in repeated pro-saccade trials in deaf participants compared to hearing controls. Bottari, Valsecchi, et al. (2011) interpreted these findings as initial evidence for a prominent role of overt attention-capture mechanisms in the deaf population. In other words, this work suggested a dominance of stimulus-driven automatic eye-movements over voluntarily controlled eye-movements; in case of conflicting information coming from stimulus- and goal-driven processes, deaf adults may prioritize sensory-related (saliency) information more than hearing controls. This interpretation is supported by neuroimaging evidence that suggests the existence of strengthened feed-forward connections between visual areas and PPC as the neural substrate mediating increased attention to the periphery in deaf adults compared to hearing controls (Bavelier et al., 2000, 2001; Scott et al., 2014). This is further consistent with evidence documenting the involvement of early stages of visual processing in mediating faster responses to abrupt visual events in deaf adults compared to hearing controls (Bottari, Caclin, et al., 2011).

1.4. The present research

The present study aims at systematically investigating the properties of the interplay between stimulus- and goal-driven components of attentional selection in deaf adults compared to

hearing controls. In particular, we examined the impact over time of salient task-irrelevant visual information on the oculomotor behavior of deaf adults. While registering participants' eye-movements, we presented deaf and hearing participants with a visual target selection task where both target and distractor always appeared at peripheral locations. Previous studies on overt target selection conducted in the hearing population consistently revealed that saccadic latencies (i.e., the time between the appearance of the display and the initiation of a saccade) provide direct insights on the relative impact on performance of stimulus- and goal-driven selection processes (van Zoest et al., 2004, 2010; van Zoest & Donk, 2005, 2008; Heimler, Pavani, Donk, & van Zoest, 2014). In these studies participants are typically instructed to search for a target (a tilted line) embedded in a homogeneous set of non-targets (i.e., vertical lines) and one additional distractor (a line tilted in the opposite direction to the target). The relative saliency of target and distractor is then further manipulated by varying the difference of these elements compared to the background non-targets. For example, van Zoest and Donk (2005) changed the color of the target or the distractor: In one third of trials the target was colored and it was the most salient stimulus in the display; in one third of trials the distractor was colored and it was the most salient stimulus in the display; and in the remaining third of trials neither the target or the distractor were colored (no unique color). van Zoest and Donk (2005) found that early initiated saccades were strongly driven by stimulus-saliency, such that they were directed to the most salient element in the display (i.e., the colored singleton), independently of whether it was the target or the distractor. Instead, later initiated saccades, starting about 250 ms following display appearance, were no longer influenced by saliency and could be directed in line with the task instruction, thus suggesting selection was goal-driven (see also van Zoest & Donk, 2008). In other words, these results ultimately indicate that the time to initiate a saccadic response plays a crucial role in determining which of the two components of attentional selection will guide participants' behavior.

Importantly, to further test potential differences in the relative contribution of stimulus- and goal-driven processes in deaf and hearing participants, we constructed a multinomial model allowing us to separately estimate the underlying temporal interplay between both types of processes (see for a similar approach: Dombrowe, Donk, Wright, Olivers, & Humphreys, 2012; Heimler et al., 2014). Based on the existing literature (see for instance Bottari, Valsecchi, et al., 2011), we predicted that peripheral salient information should have greater impact on performance in deaf adults than in hearing controls. In other words, in this scenario, we should observe a stronger contribution of stimulus-driven processes, leading to enhanced saliency capture in the deaf group, possibly paired with overall faster saccadic latencies in deaf compared to hearing adults.

An alternative possibility, however, is that deaf adults are more efficient in the deployment of voluntary overt selection strategies compared to hearing controls. The idea being that deaf adults may have become better in avoiding continuous and potentially disruptive irrelevant salient events in the scene. Such an adaptation would ultimately allow deaf individuals to behave relatively more controlled in the visual environment. In this alternative scenario, we should expect a decreased contribution of stimulus-driven processes resulting in less saliency capture in deaf compared to hearing observers. This behavioral response might also be paired with overall slower saccadic latencies in deaf compared to hearing participants, in the attempt to implement more deliberate responses (see Sladen et al., 2005).

As a final note, it is relevant to highlight that several studies have suggested that sign language proficiency might have specific influences on eye-movement control (e.g., Emmorey et al., 2009;

Watanabe et al., 2011). Emmorey et al. (2009) nicely showed that during a sign language comprehension task, face exploration's patterns differed between deaf native signers and hearing participants who were beginners in sign language. Hearing participants spent more time looking to the signing hands, whereas deaf native signers tended to keep their eyes more stable, looking predominantly at the eye-area of the signer (see Watanabe et al. (2011) for similar results not directly addressing the linguistic context but testing instead the evaluation of the emotional valence of static faces). It is currently unknown to what extent these differences in saccadic exploration could affect oculomotor behavior in target selection. Therefore, we systematically collected information regarding sign language proficiency in deaf participants. Our aim was to investigate to what extent sign language proficiency might further impact on the dynamics of stimulus- and goal-driven influences on overt target selection (see Table 2; and see Section 2.1.1.1 in Section 2.1 for a more extensive discussion of this relevant issue).

2. Experiment

2.1. Methods

2.1.1. Participants

Twenty early bilateral deaf adults (hearing loss > 70 dB in the better ear; mean age = 28 years old; SD = 5; 11 females) were recruited by the ISTC-CNR personnel to participate in this research and were tested in ISTC-CNR laboratories (Rome, Italy). Twenty hearing controls (mean age = 22.9 years old; SD = 1.9; 11 females), all students of the University of Trento, also took part in the study. All participants had normal or corrected-to normal vision. All participants signed an informed-consent form to participate in the study, which was approved by the Ethical Committee of the University of Trento. All participants received 7 Euros/hour reimbursement. Whenever needed a fluent signer explained consent procedures in Italian Sign Language (LIS).

Before starting the experiment all deaf participants completed a questionnaire aimed at collecting anamnestic information concerning their deafness characteristics and their linguistic background (see Table 1 for selected relevant information acquired through the questionnaire). In addition, deaf participants performed the Raven's Progressive Matrices test, to potentially exclude from the experiment participants with a Raven's score below pathological cut-off. Importantly, no deaf participant was

excluded from the study based on this criterion (range score for deaf participants: 106–128).

2.1.1.1. Assessment of sign language competence. As anticipated in Section 1, several studies have suggested that sign language can have specific influences on eye movement control (e.g., Emmorey et al., 2009; Watanabe et al., 2011) potentially impacting the distribution of overt attention across the visual field in deaf signers.

Most importantly, it is still unknown whether changes in oculomotor behavior documented in deaf signers, such as those reported in the work by Emmorey et al. (2009; see Section 1 for a description of their findings), are the result of the early acquisition of a sign language (i.e., before the age of 3 years old; e.g., Mayberry & Lock, 2003) or instead reflect the consequence of the massive visual training exerted by the proficient use of a sign language. To be able to further investigate this issue, we conducted a systematic assessment of deaf participants' linguistic proficiency in Italian Sign Language (LIS) through a series of linguistic tests developed ad-hoc by the ISTC-CNR group. In particular, we ultimately aimed at testing to what extent sign language proficiency exerts an effect on overt visual selection performance in deaf adults that is specifically outside a linguistic context and without the presence of social stimuli, such as face-related stimuli. Recent evidence obtained with deaf children in a rapid serial visual presentation (RSVP) task does indeed suggest that the linguistic background of deaf participants may influence their performance on covert visual attention tasks (Dye, 2014; see also Dye & Bavelier, 2010). The linguistic assessment was carried-out in a separate and dedicated experimental session. LIS assessment was conducted by deaf research assistants, with all instructions provided in LIS. All deaf participants were presented with comprehension and sentence repetition tasks. In the comprehension task, deaf participants watched a 5 min video of a story in LIS, followed by twelve signed forced-choice questions regarding the story they just saw. In the sentence repetition task, deaf participants were presented with fifteen sentences in LIS, of increasing length and difficulty. Sentences were delivered through a video, one at a time, and repeated twice if requested by the participant. Deaf participants were instructed to repeat exactly the same sentence. The entire task was recorded by a video camera. It is important to highlight that these LIS tests are part of a larger battery developed by the ISTC-CNR group to assess the level of bilingualism in deaf adults. To this aim the battery also included tests aiming at assessing proficiency in spoken and written Italian, which addressed the same linguistic domains

Table 1

Selected anamnestic information about deaf participants (as collected through the questionnaire completed at the beginning of the experiment). For the variable 'Degree of Deafness', 'Profound' means a loss ≥ 90 dB in that ear, 'Severe' means a loss ≥ 70 dB in that ear. The questionnaire was developed by the ISTC-CNR personnel.

Deaf participants	Age	Degree of deafness: right ear	Degree of deafness: left ear	Age of diagnosis (years)	Mother	Father	Hearing aid usage
1	24	Severe	Severe	1	Hearing	Hearing	2 Ears
2	43	Profound	Profound	2	Hearing	Hearing	No
3	23	Severe	Severe	Birth	Deaf	Deaf	No
4	27	Profound	Severe	Birth	Deaf	Deaf	1 Ear
5	22	Severe	Severe	3	Deaf	Deaf	2 Ears
6	23	Profound	Profound	Birth	Deaf	Deaf	No
7	34	Severe	Severe	2	Hearing	Hearing	2 Ears
8	25	Profound	Profound	Birth	Deaf	Deaf	No
9	32	Severe	Severe	2	Hearing	Hearing	2 Ears
10	29	Profound	Profound	2	Hearing	Hearing	2 Ears
11	26	Profound	Profound	5/6 Months	Hearing	Hearing	2 Ears
12	32	Profound	Profound	Birth	Hearing	Hearing	No
13	24	Profound	Profound	6/8 Months	Hearing	Hearing	2 Ears
14	33	Profound	Profound	Birth	Hearing	Hearing	1 Ear
15	25	Severe	Profound	3	Hearing	Hearing	2 Ears
16	29	Profound	Severe	Birth	Deaf	Deaf	No
17	27	Profound	Profound	2	Hearing	Hearing	1 Ear
18	25	Profound	Profound	3	Hearing	Hearing	2 Ears
19	29	Profound	Profound	1	Hearing	Hearing	2 Ears

Table 2

Age of acquisition of Italian Sign Language (AoA of LIS) self-reported by deaf participants and z-scores of deaf participants in the LIS tests. In the column where AoA of LIS are reported, ‘-’ means that sign language was unknown. In all the other columns, ‘-’ means that a particular value is missing. These values were used in correlation analyses with the individual mean saccadic latencies.

Deaf participants	AoA of LIS (years)	LIS comprehension	LIS sentence repetition
1	22	–	–
2	17	0.14	–0.53
3	Native	0.14	0.02
4	Native	0.14	–0.53
5	7	0.14	–0.71
6	Native	1.18	0.75
7	18	0.14	0.38
8	Native	1.69	1.29
9	6	–0.37	0.57
10	20	0.14	–1.25
11	26	–1.92	–0.53
12	2	–0.89	0.75
13	–	–1.92	–2.71
14	15	–1.41	0.38
15	20	0.14	0.02
16	Native	0.66	1.29
17	18	0.14	0.93
18	21	1.18	–0.71
19	24	0.66	0.57

covered by the tasks developed for LIS assessment. Specific results of this comprehensive linguistic assessment will be described in full details in future reports.

In the present work LIS scores (see Table 2) were only used for correlational analyses with the performance of deaf participants in the overt visual selection paradigm (except for participant 1 for which linguistic measures could not be acquired).

2.1.2. Experimental set-up

A Dell PC controlled the timing of the events and generated the stimuli. Eye movements were recorded through an EyeLink tracker (EyeLink 1000 Desktop Remote, SR Research) with 1000 Hz temporal resolution and 0.05° spatial resolution. The system uses an infrared video-based tracking technology to compute the pupil center and pupil size of both eyes. Eye-movements from the right eye were recorded, but viewing was binocular. The monitor used to display stimuli was a 19-in. SVGA color monitor, with 1024 × 768 pixels resolution and a 75 Hz refresh rate. All participants were tested in a dimly lit room with their head resting on a chinrest. The monitor was located at eye level, 60 cm from the chinrest.

In each trial, the display comprised 165 segments, arranged in a 15 × 11 matrix and covering a raster width of 30.7° × 25° of visual angle. Embedded in each display there were one target and one distractor, each defined in the orientation dimension. Across the whole experiment, the target was tilted in a pre-specified direction (e.g., 45° to the right), whereas the distractor was tilted in the opposite direction with respect to the target (e.g., 45° to the left). All remaining segments were vertically oriented (non-targets). While vertical non-targets were always white, stimulus saliency of target and distractor was manipulated through color across experimental trials. In one third of trials, the target was colored red and the distractor was white (target-colored singleton), thus making the target the most salient singleton in the display. In another third of trials, the distractor was colored green and the target was white (distractor-colored singleton), thus making the distractor singleton the most salient stimulus in the display. In the remaining third of trials both target and distractor were white (no-colored singleton), thus there was no unique color singleton in the display and target and distractor were equally salient. Targets and distractors could appear at six different locations.

These six potential locations were placed at the vertex of an imaginary hexagon in such a way that, embedded in the matrix of non-targets, targets and distractors were always presented at equal eccentricity from fixation (12.4° of visual angle). The angular distance between the target and the distractor on the imaginary hexagon was always 120°; in other words, there was always one potential other location between the two elements. Segments had an approximate height of 0.9° of visual angle, an approximate width of 0.3° visual angle and were displayed on a dark gray background (see Fig. 1). Each stimulus matrix lasted for 1500 ms and was preceded by a fixation point presented for 1000 ms.

2.1.3. Procedure and experimental design

Before the experiment participants were informed that they were about to take part in a visual search task. They were shown an example of the visual display (with no-colored singleton) printed on an A4 paper, and were instructed which tilted line was the target (i.e., either right- or left-tilted line). Participants were instructed to maintain fixation until the search display appeared and then to move their eyes as fast as possible to the target, ignoring the distractor. They were also told that sometimes the target or the distractor would be colored, however it was emphasized that this information would not be informative and therefore they were instructed to ignore color information. All participants received written instructions. Further instruction, when needed, were given in Italian or in LIS, depending on participants' preferences.

Trial types were based on the full factorial combination of 6 target positions, 2 relative distractor positions (either two positions to the left or right of the target) and the 3 saliency conditions such that one repetition equaled a total of 36 trials. Trials were presented in randomized fashion across the whole experiment. Each participant performed 24 practice trials, followed by 432 experimental trials divided into 16 blocks of 27 trials each. At the end of each block participants saw on the screen the average mean latency of their initial saccades. Target and distractor orientations (i.e., right-tilted target with a left-tilted distractor and vice versa) were counterbalanced across participants. Prior to the initial recording and every 4 blocks of trials, participants viewed a calibration display consisting of nine points in a square array, which had to be fixated sequentially (standard calibration procedure of the Eye Link system).

2.2. Results

Eye movements were considered as directed to the target when the saccade fell within a radius of 6° of visual angle around the target element; eye movements were considered as directed to the distractor when the saccade fell within a radius of 6° of visual angle around the distractor element. Trials were included in the analyses only if they were directed to either the target or the distractor. This radius of tolerance allowed for the inclusion of saccadic movements that ended slightly before (saccadic undershoot) or slightly after (saccadic overshoot) the intended final location (i.e., either the target or the distractor stimulus; Kapoula & Robinson, 1986). We excluded all trials in which initial saccade latencies were below 80 ms (anticipation errors; Hearing: 1% of trials; Deaf: 1% of trials) or above 600 ms (Hearing: 4% of trials; Deaf: 6% of trials); trials that started when the eyes of the participants were more than 2.5° of visual angle away from fixation (Hearing: 4%; Deaf: 6%) as well as trials where the initial saccade missed either the location of the target or of the distractor (Hearing: 7%; Deaf: 9%). Direct between-group *t*-tests revealed no significant differences between deaf and hearing participants for any of these criteria for excluding trials. Based on the cleaned data, one deaf participant (i.e., participant 2 in Table 1) and one hearing participant were discarded from further analyses

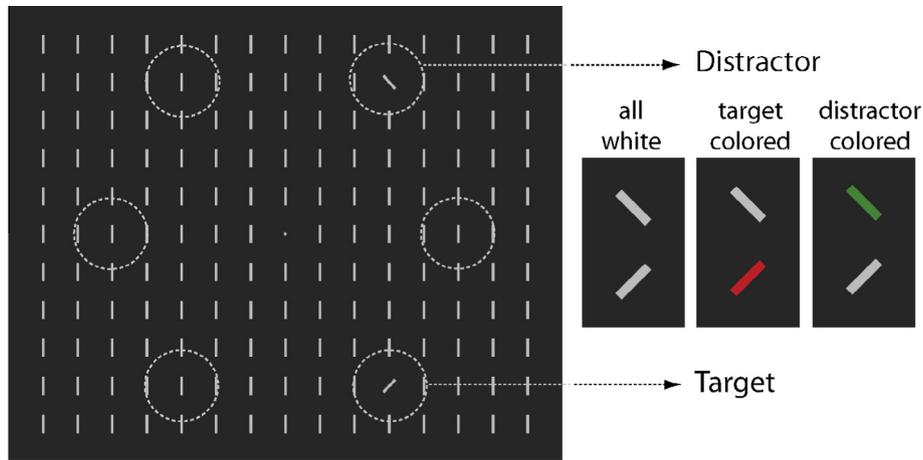


Fig. 1. An example of a stimulus-display. Target and distractor could be either both white, or only the target could be colored red, or only the distractor could be colored green. For purpose of illustration, dotted circles indicate all the possible target and distractor locations; these were not present during the experiment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

because of too many excluded trials (i.e., more than one third of all trials). Thus, subsequent analyses were conducted on nineteen hearing participants and nineteen deaf participants.

For all analyses a criterion of $\alpha = 0.05$ was established. When needed, we used Greenhouse–Geisser correction for non-sphericity. All post hoc analyses were two-tailed and have been conducted using the Tukey test.

2.2.1. Temporal dynamics analyses

In order to address our main experimental question, namely, describing the temporal dynamics of selection performance in the deaf population, we subdivided the overall distribution of the initial saccadic latencies of each participant among the three saliency-conditions and then we divided the individual latency distribution of each condition in quintiles. For each quintile of the individual latency distributions we calculated the corresponding proportion of correct saccades to the target. Then we averaged the saccadic latencies as well as the proportion of correct saccades to the target in each quintile for every participant (for a similar procedure see: van Zoest et al., 2004; van Zoest & Donk, 2005, 2008). Table 3 shows the overall mean and median saccadic latencies as well as the proportion of correct saccades to the target, separately for both groups of participants.

2.2.1.1. Saccadic latency. Saccadic latencies passed the tests assuming normality of the data-set (Jarque–Bera and Kolmogorow–Smirnov tests; p -values > 0.1). We therefore entered mean saccadic latencies into a mixed, repeated-measures ANOVA with saliency condition (colored-target; colored-distractor; no-colored singleton) and quintile (1–5) as within factors, and group (hearing; deaf) as between factor. This analysis revealed a significant main effect of group ($F(1,36) = 7.64$, $p = 0.009$, $\eta_p^2 = 0.17$) caused by overall slower saccadic latencies in the deaf group ($M = 344.79$ ms; $SE = 17.53$) compared to the hearing group ($M = 276.24$ ms; $SE = 17.53$, $p = 0.009$; see Fig. 2A–D). Also, a significant main effect of quintile emerged ($F(1.5,53.1) = 224.69$, $p < 0.01$, $\eta_p^2 = 0.86$) due to the trivial expected significant increase in saccadic latencies across quintiles (all p -values < 0.01). Finally, we observed a significant main effect of saliency condition ($F(1.7,61.1) = 6.81$, $p = 0.003$, $\eta_p^2 = 0.16$) due to overall slower saccadic latencies in the no-colored singleton saliency condition ($M = 315.32$ ms; $SE = 12.36$) compared to the other two conditions (colored-target: $M = 309.57$ ms; $SE = 12.36$; colored-distractor: $M = 306.64$ ms; $SE = 12.39$; all p -values < 0.05). No other factor was significant (all other F -values < 2.56 ; see Table 4 for mean saccadic latencies (and standard

Table 3

Median and Mean saccadic latencies (SRTs) with the corresponding standard error (SE) and mean percent of correct saccades to the target (pCorr) with the corresponding standard error (SE), for the 19 hearing and the 19 deaf participants included in all the following analyses.

		Hearing	Deaf
SRTs (ms)	Median	242	325
	Mean	274.02	377.01
	SE	22.94	24.94
pCorr (%)	Mean	0.61	0.63
	SE	0.02	0.03

errors) reported separately for quintiles, saliency conditions and group).

2.2.1.2. Proportion to the target. Percentage of correct saccades to the target did not pass the tests assuming normality of the data set (Jarque–Bera and Kolmogorow–Smirnov tests; p -values < 0.05). We therefore log-transformed the data using logit transformation. This transformed data set passed the above tests for normality (p -values > 0.1). Consequent analyses were thus performed on the log-transformed accuracy data.

Log-transformed mean percentage of correct saccades to the target were entered into a mixed, repeated-measures ANOVA with saliency condition (colored-target; colored-distractor; no-colored singleton) and quintile (1–5) as within factors, and group (hearing; deaf) as between factor. This analysis revealed significant main effects of saliency condition ($F(2,72) = 3.59$, $p = 0.03$, $\eta_p^2 = 0.09$) and of quintiles ($F(4,144) = 18.33$, $p < 0.01$, $\eta_p^2 = 0.34$), which were subsidiary to the expected significant two-way interaction between saliency condition and quintiles ($F(8,288) = 20.58$, $p < 0.01$, $\eta_p^2 = 0.36$). Most importantly, also the three-way interaction among group, saliency condition and quintiles reached significance ($F(8,288) = 5.17$, $p < 0.01$, $\eta_p^2 = 0.13$; see Fig. 3 and Table 4 where, for clarity reasons, we reported the percentage of correct saccades to the target before the logit transformation). No other factor was significant (all other F -values < 1.19).

Post-hoc analyses on the three-way interaction revealed that the effect of saliency lasted longer in hearing compared to deaf participants. Specifically, a significant difference between the colored-target and colored-distractor trials was found in the first and in the second quintiles (p -values < 0.01) for the hearing controls, whereas for the deaf participants this contrast was significant only in the first quintile ($p < 0.01$). Furthermore, visually inspection of Fig. 3

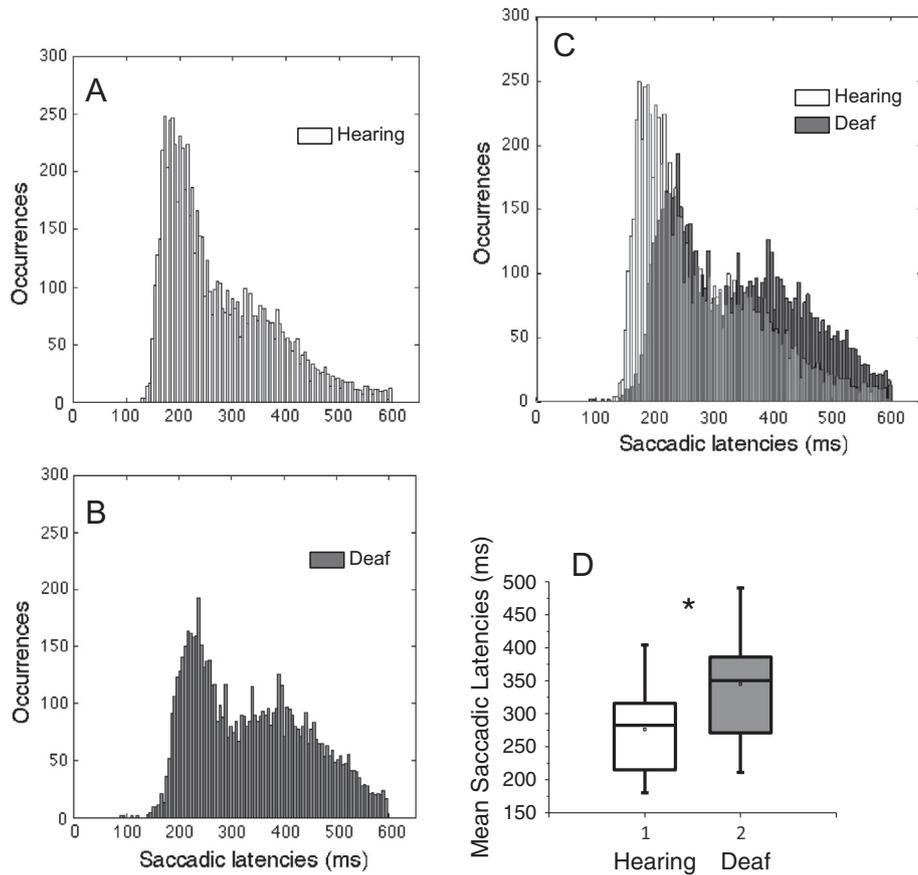


Fig. 2. Saccadic latency distributions of all included participants for all accepted trials, before the division among saliency conditions and quintiles. (A) Saccadic latency distribution of hearing participants. (B) Saccadic latency distribution of deaf participants. (C) Saccadic latency distributions of both groups of participants superimposed on each other (the lighter gray area is the area of overlapping between the two distributions). (D) Overall mean saccadic latencies of hearing participants (white box-plot) and deaf participants (gray box-plot). Deaf adults were significantly slower than hearing controls at initiating saccades.

Table 4
Mean saccadic latency (SRTs) – and standard error (SE) – and mean proportion of correct saccades to the target (pCorr) – and standard error (SE) – reported separately for each group of participants (Hearing; Deaf), each saliency condition (Target-Colored; No-colored Singleton; Distractor-Colored) and each quintile (1–5).

	Target-colored				No-colored singleton				Distractor-colored			
	SRTs (ms)	SE	pCorr	SE	SRTs (ms)	SE	pCorr	SE	SRTs (ms)	SE	pCorr	SE
<i>Hearing</i>												
Quintile 1	186.81	6.78	0.81	0.03	199.74	8.52	0.51	0.03	188.96	6.60	0.27	0.04
Quintile 2	227.09	13.67	0.67	0.06	237.48	13.24	0.52	0.03	226.25	12.32	0.41	0.06
Quintile 3	260.29	17.60	0.61	0.05	273.04	16.81	0.56	0.04	259.90	17.01	0.60	0.06
Quintile 4	304.02	20.37	0.57	0.05	313.45	19.78	0.66	0.04	303.33	19.77	0.70	0.05
Quintile 5	385.81	23.53	0.64	0.05	395.93	22.46	0.72	0.04	381.45	22.61	0.81	0.03
<i>Deaf</i>												
Quintile 1	252.94	15.73	0.69	0.05	257.59	14.55	0.55	0.03	253.53	15.20	0.41	0.05
Quintile 2	304.35	19.65	0.63	0.04	307.44	19.56	0.59	0.04	300.11	19.23	0.56	0.06
Quintile 3	341.01	21.96	0.64	0.04	339.78	21.38	0.64	0.05	335.85	21.53	0.63	0.05
Quintile 4	381.04	23.19	0.66	0.05	378.12	22.11	0.67	0.04	374.69	23.00	0.70	0.05
Quintile 5	452.39	22.23	0.70	0.04	450.69	21.43	0.72	0.04	442.35	22.80	0.69	0.05

suggests that deaf participants, compared to hearing controls, were also less captured by saliency in the first, fastest quintile (see Fig. 3C). A follow up ANOVA on performance in the fastest quintile with saliency condition as within factor and group as between factor revealed a significant two-way interaction $F(2,72) = 4.82$, $p = 0.01$, $\eta_p^2 = 0.12$).

2.3. Discussion

The present results confirmed the crucial role of time in determining attentional selection: fast initiated saccades were mainly saliency-driven, whereas later initiated saccades were more goal-

driven (e.g., van Zoest & Donk, 2005, 2008). However, intriguingly and quite unexpectedly, deaf participants showed less influence of salient information compared to hearing controls. This result suggests that there might be a fundamental difference between deaf and hearing participants concerning the strength of the underlying saliency-driven and goal-driven components contributing to overt visual selection; that is, the evolution over time of these components might differ between the two populations, with a reduced contribution of stimulus-driven processes to the oculomotor performance of deaf participants.

Nonetheless, the present results also clearly document overall slower initial saccades in deaf adults compared to hearing controls.

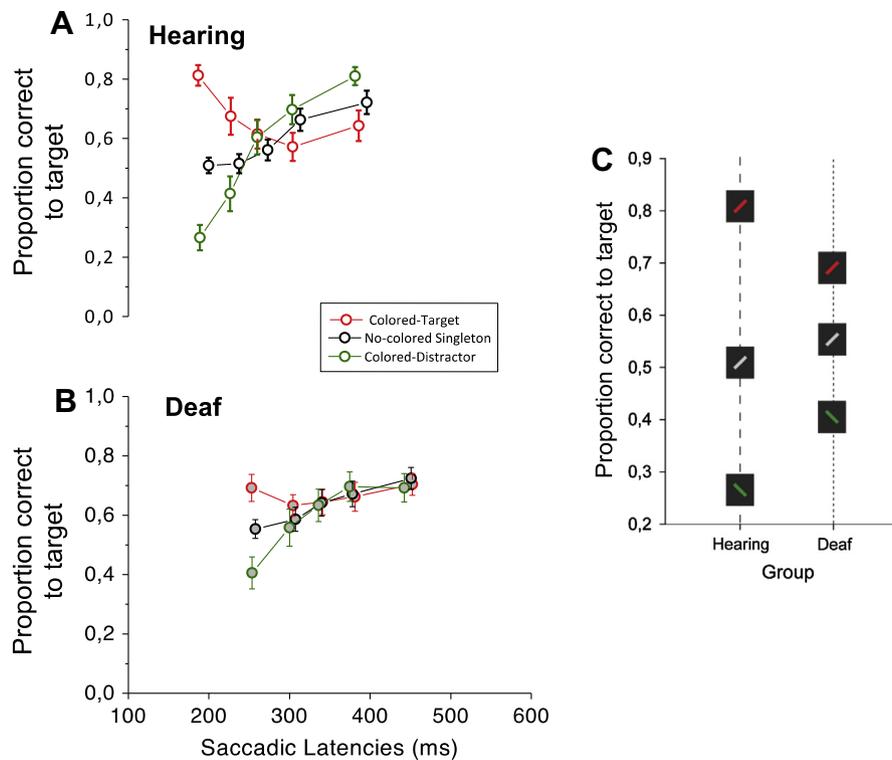


Fig. 3. Proportion of saccades correctly directed to the target as a function of saccade latency. There were 3 saliency conditions: target red (Target-Colored); target and distractor white (No-Colored Singleton); distractor green (Distractor-Colored). Circles in both graphs depict the mean accuracy (and standard errors) of participants in each one of the 5 quintiles. See Table 4 for mean and standard error of saccadic latencies and percent correct saccades to the target, for each saliency condition and each quintile, reported separately for each group. (A) Time-course of performance for hearing participants. (B) Time-course of performance for deaf participants. (C) Performance in the first and fastest quintile in the 3 saliency conditions reported separately for hearing and deaf participants. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Given the documented impact of saccadic latencies on oculomotor selection (e.g., van Zoest et al., 2004, 2010; van Zoest & Donk, 2005, 2008), it might well be that the observed differences in accuracy performance between deaf adults and hearing controls were related to differences in saccadic response latencies rather than to differences in the underlying stimulus-driven and goal-driven processes. In other words, deaf participants might appear less susceptible to saliency than hearing controls simply because they were slower than hearing controls at initiating saccades. Note that this interpretation would predict that the underlying temporal interplay between stimulus- and goal-driven processes remained unaltered as a consequence of bilateral deafness. Therefore, if this latter scenario suggests that a remarkably simple mechanism might be at play in order to maximize the efficient selection of relevant visual stimuli within the external world, namely a delay in saccadic response latencies.

With the aim to better understand the properties of the temporal interplay between stimulus- and goal-driven processes in the deaf population, we developed a multinomial model, which allowed to separately estimate the underlying contribution of saliency-driven and goal-driven processes while taking into account the differences in response latencies of both deaf and hearing participants (see for a similar approach: Dombrowe et al., 2012; Heimler et al., 2014; and see also Dodson, Prinzmetal, & Shimamura, 1998).

3. Data modeling

The model we adopted is based on three main assumptions. The first assumption is that each eye-movement is subjected to two independent biases, a goal-driven bias favoring the selection of

the target over the distractor, and a saliency-driven bias favoring the selection of the more salient singleton over the less salient one, independently of whether it was the target or the distractor. The second assumption is that for each eye-movement either of these biases can be either present or absent. In other words, each eye-movement can be the outcome of (1) a goal-driven bias only, (2) a saliency-driven bias only, (3) a combination of both response biases, or (4) the absence of both biases. Thus, the final outcome of each saccadic eye-movement is ultimately the result of either one of the aforementioned four possibilities. Finally, the third assumption is that the probability that visual selection is guided by goal-driven processes is assumed to increase with time whereas the probability that visual selection is guided by saliency-driven processes is assumed to decrease over time (e.g., Heimler et al., 2014; Jonides, 1981; Muller & Findlay, 1988; Nakayama & Mackeben, 1989; Weichselgartner & Sperling, 1987). There is much evidence that the influence of stimulus-driven and goal-driven processes on visual selection have different time courses: whereas the influence of saliency-driven processes develops rapidly after the presentation of a visual display (within about 100 ms; e.g., Posner, 1980; Theeuwes, 1992; Theeuwes, Atchley, & Kramer, 2000) followed by a slow decay, the influence of goal-driven processes evolves in a relatively slow but sustained manner (see e.g., Fig. 16, p. 1643 in Nakayama and Mackeben (1989); see further: e.g., van Zoest & Donk, 2008; Jonides, 1981; Muller & Findlay, 1988; van Zoest et al., 2004; Weichselgartner & Sperling, 1987). We choose to use an exponentially decreasing function to model the stimulus-driven component and an exponentially increasing function to model the goal-driven component. Exponential functions were chosen for mathematical simplicity (Townsend & Ashby, 1983).

3.1. Methods

3.1.1. Model parameters

Within the model, the probability that the visual system is subjected to a goal-driven bias is assumed to be a function that gradually increases over time since the presentation of a display, and it equals $G(t)$, which is given by:

$$G(t) = 1 - r_G^{-r(t-t_{0G})} \text{ for } t > t_{0G}; \quad G(t) = 0 \text{ for } t \leq t_{0G} \quad (1)$$

with t representing the time since the presentation of a display, r_G indicating the rate of the function, and t_{0G} representing the moment in time, since the presentation of the display, at which the function starts to increase. The function ranges between 0 and 1, with 0 indicating that the system is not influenced by any goal-driven bias and 1 indicating that the visual system is affected by a goal-driven bias.

When two simultaneously presented singletons differ in relative saliency (with one being more salient than the other), selection behavior may also be affected by a saliency-driven bias. The probability that the system is biased toward the most salient element in a display on the basis of stimulus-driven processes is assumed to be a decreasing function of time since the presentation of a display, and it equals $S(t)$, which is given by:

$$S(t) = r_S^{-r(t-t_{0S})} \text{ for } t > t_{0S}; \quad S(t) = 1 \text{ for } t \leq t_{0S} \quad (2)$$

with t representing the time since the presentation of a display, r_S reflecting the rate of the function, and t_{0S} indicating the moment in time since the presentation of the display, at which the function starts to decrease. The function ranges from 1 to 0, with 1 indicating that the system is biased and 0 indicating that the system is not biased by saliency.

Within the model it is assumed that the time-course of oculomotor selection is a function of $G(t)$ and $S(t)$. In particular, the tree models presented in Fig. 4 (Batchelder & Riefer, 1999) outline how $G(t)$ and $S(t)$ lead to particular responses (either an eye movement toward the target or an eye movement toward the distractor) in each of the five quintiles (Bins) of the saccadic latency distributions, separately for each of the three different saliency conditions.

Consider, for instance, the tree corresponding to the Colored-Distractor Condition (Fig. 4, right panel). If an eye movement is made in a particular quintile (Bin i), an observer may or may not have a goal-driven bias (toward the target) and may or may not have a saliency-driven bias (toward the distractor in this condition). If an observer does not have a goal-driven bias (i.e., $1 - G(t_i)$), but does have a saliency-driven bias (i.e., $S(t_i)$), the resulting response in Bin i will be an eye movement toward the most salient singleton, the distractor. If instead, an observer has only a goal-driven bias (i.e., $G(t_i)$), and does not have a stimulus-driven bias (i.e., $1 - S(t_i)$), the resulting response in Bin i will be an eye-movement toward the target, even though it is less salient than the distractor. Similarly, if an observer has neither a goal-driven bias (i.e., $1 - G(t_i)$) nor a saliency-driven bias (i.e., $1 - S(t_i)$), the resulting eye-movement will be equally likely to be directed toward the target and the distractor, with 0.5 probability. Finally, the model also accounts for the possibility that both biases are present. If an observer has both biases (i.e., $S(t_i)$ and $G(t_i)$), the saccade ends with equal probability either on the target or on the distractor.

The overall probability of a particular response in a particular Bin i equals the sum of the paths leading to that response in Bin i . For instance, the probability to correctly saccade toward the target in the Bin i , $p(T_i)$, of the Colored-Distractor Condition is given by:

$$p(T_i) = (G(t_i) * S(t_i) * 0.5) + (G(t_i) * (1 - S(t_i))) + ((1 - G(t_i)) * (1 - S(t_i)) * 0.5) \quad (3)$$

$S(t)$ and $G(t)$ functions cannot be directly observed, but based on these tree diagrams (Fig. 4), it is possible to estimate the parameters of these functions, namely, the slopes of the two functions (r_G , r_S) and their onsets (t_{0G} , t_{0S}), separately per condition (colored-target, colored-distractor, no-colored singleton) and group (hearing and deaf group). If the fitting of the model results in different underlying stimulus- and goal-driven functions in deaf and hearing participants, that is different parameters for each group, we could conclude that there might most likely be a difference in the relative contribution of the underlying processing functions to the performance of the two groups. If instead, the model results suggest equal processing functions between groups, that is the same parameters between groups, we may conclude that early deafness does not intrinsically modify the underlying evolution over time of stimulus- and goal-driven processes.

3.2. Results: Model fitting

On the basis of the averaged binned proportions of target saccades ($p(T_i)$), the averaged binned proportions of distractor saccades ($p(D_i)$), and the corresponding averaged saccadic latencies, we estimated $G(t)$ and $S(t)$ separately per condition and group. For each group, there were 3 saliency conditions (Colored-Target, No-colored Singleton, and Colored-Distractor), 5 quintiles (1–5), and 2 possible response categories (Target saccade and Distractor saccade), resulting in $3 \times 5 \times 2 = 30$ cells in each group data matrix. With data organized in this way, we fitted the tree models depicted in Fig. 4 to the data, consisting of the frequencies of responses¹ in the different cells of the group data matrices with their concomitant saccadic latencies, either assuming $G(t)$ and $S(t)$ to be different for both groups (unequal-groups model fits) or assuming $G(t)$ and $S(t)$ to be equal for both groups (equal-groups model fits).

In the full unequal-groups model fits, r_G , t_{0G} , r_S , and t_{0S} were separately estimated for each condition and each group, with 10 free parameters per group, namely, r_G , t_{0G} , r_S , and t_{0S} were separately estimated in the Colored-Target condition, r_G and t_{0G} were estimated in the No-Colored Singleton condition, and r_S and t_{0S} were estimated in the Colored-Distractor condition, resulting in a total of 20 free parameters. In the full equal-groups model fits, r_G , t_{0G} , r_S , and t_{0S} were separately estimated for each condition but equalized over the two groups, resulting in a total of 10 free parameters.

In the restricted unequal-groups model fits, r_G , t_{0G} , r_S , and t_{0S} were assumed to be equal across conditions (i.e., r_G and t_{0G} in the Colored-Target condition = r_G and t_{0G} in the No-Colored Singleton condition = r_G and t_{0G} in the Colored-Distractor condition, and r_S and t_{0S} in the Colored-Target condition = r_S and t_{0S} in the Colored-Distractor condition), but different between groups, thus resulting in 4 free parameters per group and a total of 8 free parameters. In the restricted equal-groups model fits, r_G , t_{0G} , r_S , and t_{0S} were assumed to be equal across conditions and groups resulting in a total of 4 free parameters.

To optimize parameters estimation, we used Maximum Likelihood Estimation (MLE), with the constraint that all parameter values were larger than or equal to 0 and the rate parameters smaller than 1. The maximum likelihood estimates are those parameter that maximize $\ln(L)$ which is given by:

$$\ln(L) = \sum_j f_j * \ln(p_j) \quad (4)$$

¹ To obtain the averaged frequencies of responses, namely, the numbers of target saccades and the numbers of distractor saccades in the different bins of the different saliency conditions, we multiplied the averaged proportions of target saccades and distractor saccades, as depicted in Fig. 3, by the averaged numbers of trials in each bin of each condition.

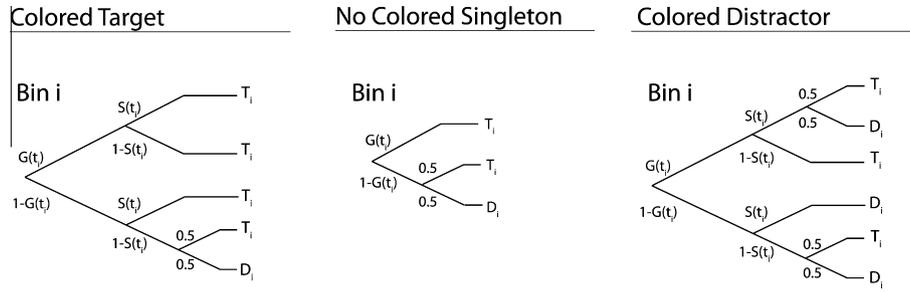


Fig. 4. Tree diagrams depicting how $G(t_i)$ and $S(t_i)$ determine the occurrence of saccades toward the target (T_i) or toward the distractor (D_i) in each quintile (Bin i) of each saliency condition. $G(t_i)$ corresponds to the probability that the visual system is affected by a goal-driven bias at time t_i which equals the averaged saccadic latency of the corresponding Bin i of the response latency distribution; $S(t_i)$ corresponds to the probability that the visual system is affected by a saliency-driven bias at time t_i which equals the averaged saccadic latency of the corresponding Bin i of the response latency distribution.

Table 5

Parameter estimates derived from the four best-fitting models, reported separately for the hearing and for the deaf group along with the numbers of free parameters (ν), the degrees of freedom (df), the G^2 values, and the corresponding critical χ^2 values at $\alpha = .05$.

	Colored-target				No-colored singleton		Colored-distractor				ν	df	G^2	Critical χ^2 value ($\alpha = .05$)
	r_G	t_{0G}	r_S	t_{0S}	r_G	t_{0G}	r_G	t_{0G}	r_S	t_{0S}				
<i>Full different-groups model</i>														
Hearing	0.014	153	0.003	297	0.004	228	0.004	0	0.012	198	20	10	0.50	18.31
Deaf	0.032	213	0.002	165	0.003	219	0.021	218	0.001	0				
<i>Full equal-groups model</i>														
Hearing	0.014	155	0.002	227	0.003	221	0.002	0	0.013	169	10	20	5.77	31.41
Deaf	0.014	155	0.002	227	0.003	221	0.002	0	0.013	169				
<i>Restricted different-groups model</i>														
Hearing	0.030	169	0.003	202	0.003	202	0.030	169	0.003	202	8	22	4.83	36.78
Deaf	0.033	218	0.002	202	0.002	202	0.033	218	0.002	202				
<i>Restricted equal-groups model</i>														
Hearing	0.023	163	0.002	180	0.002	180	0.023	163	0.002	180	4	26	7.71	38.89
Deaf	0.023	163	0.002	180	0.002	180	0.023	163	0.002	180				

with f_j referring to the response frequency in cell j of the group data matrices and p_j to the probability at the response according to the model. $\ln(L)$ was maximized using the Solver function in Excel. Table 3 depicts the parameter estimates obtained from the best-fitting models along with the number of free parameters per model, the degrees of freedom, and the G^2 values² (see also Dodson et al., 1998).

As depicted in Table 5, all values of G^2 were well below the corresponding critical χ^2 values at an alpha level of .05, for all the four models tested. Table 5 also shows that the G^2 values corresponding to the equal-groups model fits are larger than those corresponding to the unequal-groups model fits. This latter result was anticipated considering the fact that the numbers of free parameters in the equal-groups model fits are half of those in the unequal-groups models fits, thus decreasing the corresponding goodness of fit. To determine whether the differences between these two models were statistically different – in other words, whether the unequal-groups model fits described the data significantly better than the equal-groups model fits, we subtracted the G^2 values obtained with the unequal-groups model fits from those

obtained with the equal-groups model fits (Dodson et al., 1998). These resulting differences can be perceived as χ^2 values with degrees of freedom (df) corresponding to the differences in the numbers of free parameters between the models. The resulting differences were $\Delta G^2 = 5.28$ for the full model fits (critical χ^2 value ($df = 10, \alpha = .05$) = 18.31) and $\Delta G^2 = 2.88$ for the restricted model fits (critical χ^2 value ($df = 4, \alpha = .05$) = 9.49). Both these difference values were well below the corresponding critical χ^2 values at an alpha level of .05. These results then suggest that both for the full and for the restricted models, the unequal-groups models do not outperform the equal-groups models. This ultimately indicates that the simplest models that can adequately fit our data are those assuming that the groups are equal with respect to the underlying attentional mechanisms.

We also performed a final similar comparison between the differences in the goodness-of-fit of the most parsimonious model and the least parsimonious model – that is, the restricted equal-groups model vs. the full unequal-groups model. This comparison revealed no reliable difference: $\Delta G^2 = 7.22$ (critical χ^2 value ($df = 16, \alpha = .05$) = 26.30). Thus, suggesting that the simplest model that can adequately fit the behavioral data pattern is the restricted equal-groups model. The critical main assumption of this model is that the underlying $G(t)$ and $S(t)$ functions develop similarly in hearing and deaf participants and do not vary across conditions.

For illustrative purposes, Fig. 5 shows the observed and predicted proportions of correct saccades to the target for the least and most parsimonious model, that is, the full unequal-groups mode and the

² The goodness-of-fit measure G^2 is given by: $G^2 = \sum_j (2 * f_j) * \ln(\frac{f_j}{p_j})$, with f_j referring to the observed response frequency in cell j of the group data matrices and p_j to the predicted response frequency in cell j according to the model. The value of G^2 can be interpreted as a χ^2 value (the smaller the G^2 values, the better the fit). Furthermore, in order to accept a model as adequate, G^2 values should be smaller than the corresponding χ^2 value.

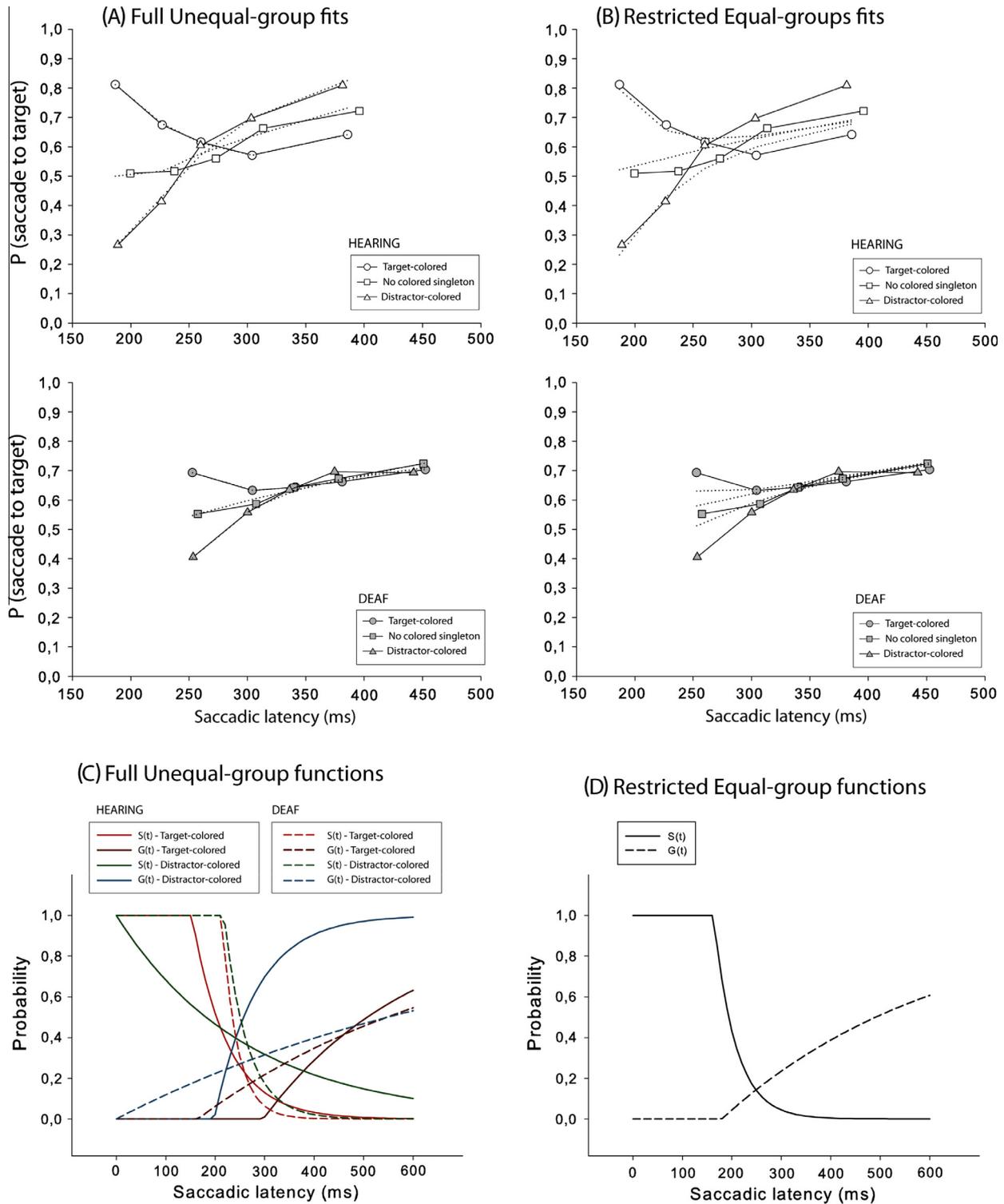


Fig. 5. Observed proportions of corrected saccades to the target (solid lines) as a function of Saccadic latency as depicted in Fig. 3, together with the predicted proportions of correct saccades to the target (dashed lines) depicted separately per bin (quintile), saliency condition, and group for the full unequal-groups model (A) and for the restricted equal-groups model (B), along with the corresponding best-fitting $S(t)$ and $G(t)$ functions derived from the full unequal-groups model (C) and from the restricted equal-groups model (D).

restricted equal-groups model respectively, along with the corresponding underlying functions estimated by the models.

3.3. Discussion of modeling results

First of all, the present findings corroborate previous results suggesting that visual selection behaviors can be well described

as the outcomes of two dissociable components: a fast decaying stimulus-driven component and a gradually increasing goal-driven component (e.g., Dombrowe et al., 2012; Heimler et al., 2014; Jonides, 1981; Muller & Findlay, 1988; Nakayama & Mackeben, 1989; Weichselgartner & Sperling, 1987).

Furthermore, the comparisons between models strongly suggested that the development over time of the underlying

goal-driven and stimulus-driven components is not intrinsically modified by early bilateral deafness. Our analyses revealed that the observed behavioral pattern could be reliably explained by assuming equal parameters describing the underlying two processing functions both across groups and saliency conditions. Importantly, this latter result, clearly suggests that the decreased influence of saliency that we reported in deaf participants (see Sections 2.2.1.2 and 2.3) did not result from a reduction in the strength of stimulus-driven processes. Instead, the aforementioned difference in saliency seems to be only the result of the delayed saccadic behaviors of deaf adults, which in turn modified the amount of saliency-capture in the responses, without altering the underlying temporal dynamics of stimulus-driven and goal-driven components. Ultimately then, the present results further corroborate the crucial role of time in determining the outcome of saccadic selection (e.g., van Zoest et al., 2004; van Zoest & Donk, 2005, 2008).

4. Further analyses

4.1. Explaining the slower responses of deaf participants

To further investigate the origin of the overall slow-down of saccadic responses we observed in deaf participants, we conducted a series of Analyses of Covariance (ANCOVAs) with the mean saccadic latencies of each deaf participant as dependent variable, and the age of acquisition of LIS, the score obtained in LIS comprehension test, and the score obtained in LIS sentence repetition test as covariates (see Table 2). However, none of these covariates predicted saccadic latencies of deaf participants (all F -values < 1.62).

In addition, we also conducted an ANCOVA on the same dependent variable but using as covariate the scores obtained in the Raven Matrices test. Neither this covariate did reliably predict saccadic latencies of deaf participants ($p = 0.12$).

Finally, we wanted to exclude a role of age at the moment of testing as a covariate to predict the saccadic latencies outcome. Therefore we conducted an ANCOVA with the mean saccadic latencies of all participants as dependent variable, age at the moment of testing as covariate, and group (deaf; hearing) as between-group factor. This analysis revealed only a slightly significant main effect of group ($F(1, 35) = 3.76, p = 0.06, \eta_p^2 = 0.10$) due to the fact that the deaf group tended to be older than the hearing group (hearing: mean age = 22.9 years old; SD = 1.9; deaf: mean age = 28 years old; SD = 5). However, the effect of age as a covariate for predicting variations in saccadic latencies was not significant ($p = 0.56$).

4.2. Disengaging attention from distractor

The paradigm we adopted also allowed to assess whether deaf participants were quicker than hearing controls at disengaging attention from the distractor when the eyes were first incorrectly directed to the distractor singleton (see for instance Chen et al. (2006) and Colmenero et al. (2004) for results on covert attention mechanisms suggesting faster re-direction of peripheral visual attention in deaf adults compared to hearing controls). To this aim we conducted a mixed, repeated-measures ANOVA on the fixation-duration of the first saccades ending on the distractor, when the second saccade was correctly directed to the target, with saliency condition (colored-target; colored-distractor; no-colored singleton) as within factor and group as between factor (hearing; deaf). This analysis revealed no significant main effect or interactions (all F -values < 1.93).

5. General discussion

In the present study we tested a group of deaf adults and a group of hearing controls in an overt saccadic target-selection task.

The aim of the study was to characterize the temporal dynamics of the interplay between stimulus-driven and goal-driven selection in the deaf population, and to investigate to what extent hearing impairment and sign language proficiency may influence their interaction.

By taking into account the crucial factor of time, two important differences emerged in the behavioral performance of deaf adults compared to hearing controls. First, deaf adults were overall slower than hearing controls at initiating their first saccadic responses; second, deaf adults were influenced by saliency to a lesser extent compared to hearing controls. To establish whether the aforementioned differences in behavioral performance reflected a difference in the underlying development of saliency-driven and goal-driven selection components over time in the two populations, we fitted a multinomial model to our data (see Dombrowe et al. (2012) and Heimler et al. (2014) for a similar approach). This model used the averaged frequencies of responses and the mean saccadic latencies in each quintile and for each of the three saliency manipulations (i.e., colored-target; colored-distractor; no-colored singleton) to estimate and describe the underlying development of saliency-driven and goal-driven functions over time. Using this model, we tried to disambiguate whether or not the decreased influence of saliency for deaf participants could be explained by the presence of a reduction in the underlying stimulus-driven processes. A direct comparison between the goodness of fit of the relevant models showed that this was not the case. Our analyses showed that the most parsimonious model is the one that assumes equal parameters between the two groups and across the three saliency-conditions. Even though the number of free parameters was lowest in this model compared to the other models, our simplest model was able to successfully explain the observed behavioral performance. These results, in turn, indicate that the postponement of saccadic responses most likely led to the reported reduced influence of saliency in deaf compared to hearing observers. Importantly, we also showed that this slow-down of saccadic latencies in deaf observers could not be explained by any of the linguistic measures we collected or by any other available measure (i.e., Raven Matrices Test scores; age of participants). Therefore, such saccadic delay seemed to depend on early-deafness per se.

5.1. Control over stimulus-driven behavior

The first important conclusion that emerges from the present findings is that early auditory deprivation does not necessarily lead to the prioritization of stimulus- over goal-driven mechanisms of selection. As pointed out in Section 1, several pieces of evidence hint to the possibility that deaf adults may prioritize stimulus-driven over goal-driven processes compared to hearing controls (Bavelier et al., 2000, 2001; Bottari, Valsecchi, et al., 2011; Scott et al., 2014). In addition, many studies reported faster responses in deaf adults compared to hearing controls in several visual behavioral tasks that involve abrupt and salient visual events (e.g., simple detection: Bottari et al., 2010; Heimler & Pavani, 2014; Loke & Song, 1991; discrimination of visual motion direction: Neville & Lawson, 1987; Hauthal, Sandmann, Debener, & Thorne, 2013; visual temporal order judgment: Nava, Bottari, Zampini, & Pavani, 2008). In certain visual discrimination tasks, speed accuracy trade-offs have been reported in the deaf population when deaf participants were required to be as fast and as accurate as possible (e.g., Bottari et al., 2010). Most importantly for the present context is a recent EEG study that has linked the speeded visual behavior of deaf adults to changes occurring at very early stages of visual processing, thus suggesting faster visual processing in deaf compared to hearing adults (Bottari, Caclin, et al., 2011; see also Hauthal, Thorne, et al., 2013). Contrary to what it would have been predicted based on these previous findings the

present results suggest that faster release of responses to salient visual events can be efficiently avoided by deaf adults (see also Sladen et al., 2005). In other words, these results ultimately suggest that the documented faster visual processing are not inevitable but can be successfully inhibited by deaf adults (see Section 5.4), possibly facilitating to some extent the implementation of goal-driven behaviors (see also Sladen et al., 2005). In fact, the present study showed that deaf adults were less influenced by saliency than hearing controls, and that this reduced saliency capture depended from the delayed saccadic latencies of the deaf group.

The documented delay in oculomotor behavior of deaf adults may be the result of an adaptive outcome of deafness-related plasticity aimed at avoiding potentially disruptive capture by irrelevant salient peripheral visual stimuli in the environment (see also Dye and Hauser (2014) for converging conclusions). This adaptation would allow for a more controlled deployment of selection and would benefit the efficiency of visual information processing in deaf individuals. Based on the present results, though, we cannot disambiguate the extent to which this type of adaptation is intentional and strategic in nature or it is instead a more automatic process. In other words, the question that remains open is whether deaf adults are able to prevent disruptive saliency capture in every situation or whether this ability may be context-dependent, thus essentially depending on the nature of the saliency manipulation (see also Section 5.5). Future studies then, may aim at further characterizing the intrinsic nature of this adaptive delayed oculomotor behavior.

The general saccadic slowing observed in our sample of deaf observers may also have been influenced by an increased motivation of this group of participants to perform well in the task: Delaying the saccadic responses allowed participants to be more accurate. However, based on the instructions that were given, we think this interpretation is unlikely because participants were strongly encouraged to prioritize speed and feedback was provided on saccadic latency only. Therefore, higher motivation would have most plausibly resulted in shorter rather than longer saccadic latencies in more motivated participants.

5.2. Spatial selection and feature-based selection in the deaf population

The present results seem to be at odds with a previous eye-movement study that has been conducted in the deaf population that concluded that deaf adults might prioritize stimulus-driven over goal-driven selection behaviors (Bottari, Valsecchi, et al., 2011). Bottari, Valsecchi, et al. (2011) presented deaf and hearing participants with a pro/anti saccade task and they reported that deaf participants made more mistakes in the anti-saccade trials and they were also faster in repeated pro-saccade trials compared to hearing controls (see Section 1 for further details on the paradigm). The discrepancy between the study by Bottari, Valsecchi, et al. (2011) and the present results may be explained by the different demands in the two paradigms. Specifically, the pro/anti saccade task may tap into spatial selection mechanisms as it requires participants to prioritize certain locations in space. Accuracy here primarily depends on the correct execution of a saccadic response to a spatial location. While there may be competition between spatial locations in this task, there is no direct competition between visual stimuli. Instead, in the present study we focused on feature-based selection in visual search. Participants were required to search and make an eye movement to a specific pre-defined stimulus (i.e., right/left-tilted singleton). The target competed for selection with a number of non-targets and an additional distractor in the display. The divergence of our data with those reported by Bottari, Valsecchi, et al. (2011) might

in turn indicate that spatial and feature-based selection may be reorganized differently as a consequence of deafness.

Another aspect of the present findings that may corroborate the latter conclusion is the fact that we found no difference in the time needed to disengage attention from distractors between deaf and hearing participants. This result is in contrast with previous covert attention studies suggesting faster re-orienting of peripheral visual attention in the deaf population (Chen et al., 2006; Colmenero et al., 2004). However, these previous studies focused on spatial-orienting of attention, and not on feature-based attentional selection as in the present case.

More generally, almost all previous studies that have investigated attentional selection processes in the deaf population have primarily focused on spatial orienting of attention (e.g., Bottari, Caclin, et al., 2011; Chen et al., 2006, 2010; Neville & Lawson, 1987; Proksch & Bavelier, 2002; see for a review Bavelier et al., 2006). The present study represents one of the few studies that targeted feature-based selection (see also Stivalet et al., 1998). Future studies may want to further investigate the potential differences between these two aspects of attentional selection to further characterize the reorganization of visual attention in the deaf population.

5.3. Enhanced attentional resources devoted to visual periphery do not necessarily result in increased saliency processing

Several previous studies have demonstrated that deaf adults allocate more covert attentional resources to the visual periphery compared to hearing controls (Chen et al., 2010; Proksch & Bavelier, 2002). In particular, these studies showed that deaf participants were slower than hearing controls when the target appeared together with peripheral distractors that differed in shape. These results were taken to suggest that deaf adults devote more attentional resources to the periphery of the visual field compared to hearing controls (Proksch & Bavelier, 2002). However, how this increased peripheral attentional deployment would express itself in overt attention behavior has not yet been directly investigated. One possibility is that these enhanced peripheral attentional resources would result in increased overt automatic capture by salient peripheral visual events in deaf adults compared to hearing controls (for example, see Belopolsky, Zwaan, and Theewes (2007) for results in this direction in the hearing population). Based on this explanation, in the present task we would have expected deaf adults to have made more saccades to the irrelevant salient singletons in the periphery compared to hearing controls. Instead, deaf adults showed the opposite pattern of results. The present findings, in turn, suggest that the enhanced covert attention to the periphery repeatedly reported in the deaf population (Chen et al., 2010; Proksch & Bavelier, 2002) seems to lead to the inhibition rather than to the facilitation of oculomotor responses to salient but irrelevant peripheral events.

Indirect converging evidence supporting this latter proposal comes from another recent eye-movement study that compared deaf and hearing observers in a reading task (Bélanger et al., 2012). Bélanger et al. (2012) found that proficient deaf readers made longer forward-saccades (i.e., subsequent saccades planned to proceed in reading a text) compared to matched-reading-skilled hearing adults. The authors argue that saccades are planned based on the information gathered through peripheral vision (see also Rayner, 2009) and consider saccadic planning as a good indirect measure reflecting the distribution of visual attention over space. Bélanger et al. (2012) propose that the longer forward saccades of deaf adults compared to hearing controls may be the result of the availability of a wider attentional field from which deaf adults can gather information (Bélanger et al., 2012). Bélanger et al. (2012) did not report saccadic latencies of participants, thus we

do not know whether deaf readers also took longer than hearing readers in planning their saccades, as it is the case in the present work. In other words, it remains an open issue whether the increased peripheral attentional resources may be a systematic factor of delay for oculomotor behavior. Future studies on the distribution of overt attentional resources in deaf observers could further characterize the interplay between covert and overt attention deployment in this population.

5.4. Possible plastic modifications underlying the present results

The present results are particularly interesting in light of the evidence that has related experience-dependent changes within the visual system of deaf adults to feed-forward visual processing (e.g., Bottari, Caclin, et al., 2011; Codina et al., 2011; Scott et al., 2014). This literature on the neural correlates of deafness motivated our initial prediction toward increased saliency capture in deaf adults compared to hearing controls. However, our findings highlight the possibility that experience-dependent plasticity in deafness may exert top-down changes in the reorganized visual system, in addition to the well-documented bottom-up modifications of visual processing. In fact, the delayed saccadic latencies we reported in deaf adults may depend upon strengthened modulatory feedback connections to visual areas in deaf compared to hearing adults. Ample evidence now converges on the idea that the Fronto-Parietal Attentional Network (FPAN) mediates stimulus- and goal-driven attentional selection processes (see Ptak (2012) for a review). This network comprises PPC, premotor and prefrontal cortex (as well as FEF), which are reciprocally interconnected through the superior longitudinal fasciculus (SLF). In addition, PPC and FEF are also connected to visual areas from which they receive sensory information and to which they send back goal-driven information (Ptak, 2012). Therefore these two latter areas have been proposed as candidate regions where stimulus- and goal-driven information may converge (e.g., Jerde et al., 2012; Ipata, Gee, Goldberg, & Bisley, 2006; Ptak, Camen, Morand, & Schneider, 2011). Importantly for the present context, both PPC and FEF have been shown to be active during saccadic planning (see for instance Ptak et al., 2011). We speculate that the delayed oculomotor behavior we reported for deaf compared to hearing participants may stem from strengthened feedback connections between FEF and visual cortices and/or between PPC and visual cortices. Strengthened connections between PPC and visual cortices have been already documented in the deaf population, albeit such strengthening has been described as mediating primarily feed-forward visual processing (Bavelier et al., 2000, 2001; Scott et al., 2014). Future studies could more directly investigate this proposal that the reverse connections are similarly enhanced in the deaf population.

Interestingly, a recent study comparing deaf and hearing children in a continuous performance test (Dye & Hauser, 2014) provides indirect evidence for the existence of such top-down modifications in the deaf population. Dye and Hauser (2014) showed that young deaf children (6–8 years old) were more distracted by peripheral visual distractors compared to hearing children, but the disadvantage in performance vanished in the older deaf group (9–13 years old) (Dye & Hauser, 2014). This latter behavioral pattern may be mediated by the same neural mechanism we are proposing. Furthermore, these results may trace the developmental trajectory of this plastic change by documenting that the strengthening of top-down connections to visual areas takes time to become effective. Finally, this latter work together with the present results further corroborate the possibility that such strengthened top-down connections may be fundamental in

order to limit the potential disruptive effects of bottom-up visual reorganizations. The development of such top-down modifications would ultimately allow for a considerable degree of flexibility in the reorganized visual system of deaf adults.

Importantly, the present findings highlight the necessity to embrace a more comprehensive approach when aiming at unraveling experience-dependent plasticity exerted by bilateral deafness – or more generally plasticity exerted by any form of sensory deprivation. Such an approach should not be limited to a specific, selective interest toward sensory processing but it should consider instead, the wholesale reorganization of multiple brain networks within the sensory deprived brain.

5.5. Dorsal vs. ventral features of distracting stimuli

Finally, another aspect of the present findings that certainly needs further investigation is to what extent oculomotor behavior of deaf participants is influenced by the nature of the visual information. In the present study we chose to manipulate saliency through color information. Color is often categorized as a ventral visual stream feature. However, several studies have proposed that only visual functions and visual properties processed by the dorsal visual stream are subjected to reorganization as a consequence of early bilateral deafness (Armstrong, Neville, Hillyard, & Mitchell, 2002; Bavelier & Neville, 2002). The present data seem to suggest that this may not be necessarily the case and that also ventral-stream visual stimulations may trigger plastic modifications in the deaf population (see also Vachon et al. (2013) for results showing plasticity in deaf adults using visual stimuli that activate the ventral visual stream).

Future research may focus on whether or not delayed saccadic latencies and reduced saliency capture are observed when saliency is manipulated using dorsal-stream visual stimuli for which behavioral advantages and bottom-up plastic changes have been documented in deaf individuals compared to hearing controls (e.g., abrupt onsets see Bottari, Caclin, et al., 2011; moving stimuli see Codina et al., 2011; Fine, Finney, Boynton, & Dobkins, 2005; Shiell et al., 2014). Such an approach would permit to further address this critical issue, and to shed further light on the neural mechanisms mediating the delayed saccadic behavior we have reported.

6. Conclusions

In conclusion, the present findings show that deaf adults are not unavoidably biased toward salient peripheral visual stimuli in the environment. On the contrary, deaf adults appeared slower at initiating saccades compared to hearing controls and they consequently showed reduced saliency capture. We propose that this behavioral modification may be mediated by strengthened modulatory feedback connections between higher structures of the FPAN and visual areas.

This pattern of behavior is ultimately adaptive in that it helps to maximize efficient interactions with the external environment in case of early deafness. Our results suggest that a slight postponement of saccadic responses enables deaf adults to limit the distractive effect of irrelevant visual saliency. Furthermore the fact that differences in performance between the deaf and hearing participants can be entirely explained on the basis of differences in saccadic latencies also highlights the fundamental role (and value) of flexibility in plastic changes triggered by early bilateral deafness. Indeed, and importantly, this simple modulation of behavior can be easily reversed or modified based on the priority of deaf observers in every given visual task.

Acknowledgments

We thank Paolo Rossini, Alessio Di Renzo, Luca Lamano, Tommaso Luciola, Maria Biondo, Barbara Pennacchi for conducting assessment of sign language proficiency and the preliminary analyses on the sign language tests, all our deaf and hearing participants. This work was supported by a Fondazione CARITRO grant to M.C.C. and F.P. and by a PRIN grant to F.P.

References

- Agrafiotis, D., Canagarajah, N., Bull, D. R., Kyle, J., Seers, H., & Dye, M. (2006). A perceptually optimised video coding system for sign language communication at low bit rates. *Signal Processing: Image Communication*, 21(7), 531–549.
- Armstrong, B. A., Neville, H., Hillyard, S. A., & Mitchell, T. V. (2002). Auditory deprivation affects processing of motion, but not color. *Cognitive Brain Research*, 14, 422–434.
- Batchelder, W. H., & Riefer, D. M. (1999). Theoretical and empirical review of multinomial tree modeling. *Psychonomic Bulletin & Review*, 6(1), 57–86.
- Bavelier, D., Brozinsky, C., Tomman, A., Mitchell, T., Neville, H., & Liu, G. (2001). Impact of early deafness and early exposure to sign language on the cerebral organization for motion processing. *Journal of Neuroscience*, 21(22), 8931–8942.
- Bavelier, D., Dye, M. W. G., & Hauser, P. C. (2006). Do deaf individuals see better? *Trends in Cognitive Sciences*, 10(11), 512–518.
- Bavelier, D., & Neville, H. (2002). Cross-modal plasticity: Where and how? *Nature Review Neuroscience*, 138, 177–188.
- Bavelier, D., Tomman, A., Hutton, C., Mitchell, T., Corina, D. P., Liu, G., et al. (2000). Visual attention to the periphery is enhanced in congenitally deaf individuals. *Journal of Neuroscience*, 20, 1–6.
- Bélanger, N. N., & Rayner, K. (2013). Frequency and predictability effects in eye fixations for skilled and less-skilled deaf readers. *Visual Cognition*, 21(4), 477–497.
- Bélanger, N. N., Slattery, T. J., Mayberry, R. I., & Rayner, K. (2012). Skilled deaf readers have an enhanced perceptual span in reading. *Psychological Science*, 23(7), 816–823.
- Belopolsky, A. V., Zwaan, L., & Theewes, J. (2007). The size of an attentional window modulates attentional capture by color singletons. *Psychonomic Bulletin & Review*, 14(5), 934–938.
- Bosworth, R. G., & Dobkins, K. R. (2002). The effect of spatial attention on motion processing in deaf signers, hearing signers, and hearing non-signers. *Brain and Cognition*, 4, 152–169.
- Bottari, D., Caclin, A., Giard, M. H., & Pavani, F. (2011a). Changes in early cortical visual processing predict enhanced reactivity in deaf individuals. *PLoS ONE*, 6, e25607.
- Bottari, D., Nava, E., Ley, P., & Pavani, F. (2010). Enhanced reactivity to visual stimuli in deaf individuals. *Restorative Neurology & Neuroscience*, 28(2), 167–179.
- Bottari, D., Turatto, M., Bonfio, F., Abbadesse, C., Selmi, S., Beltrame, M. A., et al. (2008). Change blindness in profound deaf individuals and cochlear implant recipients. *Brain Research*, 1242, 209–218.
- Bottari, D., Valsecchi, M., & Pavani, F. (2011b). Prominent reflexive eye-movement orienting associated with deafness. *Cognitive Neuroscience*, 3(1), 8–13.
- Chen, Q., He, G., Chen, K., Jin, Z., & Mo, L. (2010). Altered spatial distribution of visual attention in near and far space after early deafness. *Neuropsychologia*, 48(9), 2693–2698.
- Chen, Q., Zhang, M., & Zhou, X. (2006). Effects of spatial distribution during inhibition or return IOR on flanker interference in hearing and congenitally deaf people. *Brain Research*, 1109, 117–127.
- Codina, C., Pascalis, O., Mody, C., Toomey, P., Rose, J., Gummer, L., et al. (2011). Visual advantage in deaf adults linked to retinal changes. *PLoS ONE*, 6(6), e20417.
- Colmenero, J. M., Catena, A., Fuentes, L. J., & Ramos, M. M. (2004). Mechanisms of visuospatial orienting in deafness. *European Journal of Cognitive Psychology*, 16(6), 791–805.
- Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, 3(3), 201–215.
- Dodson, C. S., Prinzmetal, W., & Shimamura, A. P. (1998). Using Excel to estimate parameters from observed data: An example from source memory data. *Behavior Research Methods, Instruments & Computers*, 30(3), 517–526.
- Dombrowe, I., Donk, M., Wright, H., Olivers, C. N., & Humphreys, G. W. (2012). The contribution of stimulus-driven and goal-driven mechanisms to feature-based selection in patients with spatial attention deficits. *Cognitive Neuropsychology*, 29(3), 249–274.
- Dye, M. W. G. (2014). Temporal entrainment of visual attention in children: Effects of age and deafness. *Vision Research*, 105, 29–36.
- Dye, M. W. G., Baril, D. E., & Bavelier, D. (2007). Which aspects of visual attention are changed by deafness? The case of the Attentional Network Test. *Neuropsychologia*, 45(8), 1801–1811.
- Dye, M. W. G., & Bavelier, D. (2010). Attentional enhancements and deficits in deaf populations: An integrative review. *Restorative Neurology and Neuroscience*, 28, 181–192.
- Dye, M. W. G., & Hauser, P. C. (2014). Sustained attention, selective attention and cognitive control in deaf and hearing children. *Hearing Research*, 309, 94–102.
- Dye, M. W. G., Hauser, P. C., & Bavelier, D. (2009). Is visual attention in deaf individuals enhanced or deficient? The case of the useful field of view. *PLoS ONE*, 4(5), e5640. <http://dx.doi.org/10.1371/journal.pone.0005640>.
- Emmorey, K., Thompson, R., & Colvin, R. (2009). Eye gaze during comprehension of American Sign Language by native and beginning signers. *Journal of Deaf Studies and Deaf Education*, 14, 237–243.
- Everling, S., & Fischer, B. (1998). The antisaccade: A review of basic research and clinical studies. *Neuropsychologia*, 36, 885–899.
- Fine, I., Finney, E. M., Boynton, G. M., & Dobkins, K. R. (2005). Comparing the effects of auditory deprivation and sign language within the auditory and visual cortex. *Journal of Cognitive Neuroscience*, 17(10), 1621–1637.
- Hallett, P. E. (1978). Primary and secondary saccades to goals defined by instructions. *Vision Research*, 18, 1279–1296.
- Hauthal, N., Neumann, M. F., & Schweinberger, S. R. (2012). Attentional spread in deaf and hearing participants: Face and object distractor processing under perceptual load. *Attention, Perception & Psychophysics*, 74, 1312–1320.
- Hauthal, N., Sandmann, P., Debener, S., & Thorne, J. D. (2013b). Visual movement perception in deaf and hearing individuals. *Advances in Cognitive Psychology*, 9, 53–61.
- Hauthal, N., Thorne, J. D., Debener, S., & Sandmann, P. (2013a). Source localisation of visual evoked potentials in congenitally deaf individuals. *Brain Topography*. <http://dx.doi.org/10.1007/s10548-013-0341-7>.
- Heimler, B., & Pavani, F. (2014). Response speed advantage for vision does not extend to touch in early deaf adults. *Experimental Brain Research*, 232(4), 1335–1341.
- Heimler, B., Pavani, F., Donk, M., & van Zoest, W. (2014). Stimulus- and goal-driven control of eye movements: Action videogame players are faster but not better. *Attention, Perception & Psychophysics*. <http://dx.doi.org/10.3758/s13414-014-0736-x>.
- Ipata, A. E., Gee, A. L., Goldberg, M. E., & Bisley, J. W. (2006). Activity in the lateral intraparietal area predicts the goal and latency of saccades in a free-viewing visual search task. *Journal of Neuroscience*, 26(14), 3656–3661.
- Jensem, C. J., Danturthi, R. S., & Burch, R. (2000). Time spent viewing captions on television programs. *American Annals of the Deaf*, 145(5), 464–468.
- Jerde, T. A., Merriam, E. P., Riggall, A. C., Hedges, J. H., & Curtis, C. E. (2012). Prioritized maps of space in human frontoparietal cortex. *Journal of Neuroscience*, 32(48), 17382–17390.
- Jonides, J. (1981). Voluntary vs. automatic control over the mind's eye's movement. In J. B. Long & A. D. Baddeley (Eds.), *Attention and performance IX*. Hillsdale, NJ: Lawrence Erlbaum Associates.
- Kapoula, Z., & Robinson, D. A. (1986). Saccadic undershoot is not inevitable: Saccades can be accurate. *Vision Research*, 26(5), 735–743.
- Kastner, S., & Ungerleider, L. G. (2000). Mechanisms of visual attention in the human cortex. *Annual Review of Neuroscience*, 23, 315–341.
- Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 451–468.
- Lavie, N., & Cox, S. (1997). On the efficiency of visual selective attention: Efficient visual search leads to inefficient distractor rejection. *Psychological Science*, 8, 395–398.
- Letourneau, S. M., & Mitchell, T. V. (2010). Gaze patterns during identity and emotion judgments in hearing adults and deaf users of American Sign Language. *Perception*, 40(5), 563–575.
- Loke, W. H., & Song, S. (1991). Central and peripheral visual processing in hearing and nonhearing individuals. *Bulletin of Psychonomic Society*, 29(5), 437–440.
- Mayberry, R. I., & Lock, E. (2003). Age constraints on first versus second language acquisition: Evidence for linguistic plasticity and epigenesis. *Brain and Language*, 87(3), 369–384.
- Maylor, E., & Lavie, N. (1998). The influence of perceptual load on age differences in selective attention. *Psychology of Aging*, 13, 563–573.
- Muir, L. J., & Richardson, I. E. (2005). Perception of sign language and its application to visual communications for deaf people. *Journal of Deaf Studies and Deaf Education*, 10(4), 390–401.
- Muller, H. J., & Findlay, J. M. (1988). The effect of visual attention of peripheral discrimination thresholds in single and multiple element displays. *Acta Psychologica*, 69(2), 129–155.
- Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research*, 29(11), 1631–1647.
- Nava, E., Bottari, D., Zampini, M., & Pavani, F. (2008). Visual temporal order judgment in profoundly deaf individuals. *Experimental Brain Research*. <http://dx.doi.org/10.1007/s00221-008-1459-9>.
- Neville, H., & Lawson, S. D. (1987). Attention to central and peripheral visual space in a movement detection task: an event-related potential and behavioural study. II. Congenitally deaf adults. *Brain Research*, 405, 268–283.
- Parasnis, I., & Samar, V. J. (1985). Parafoveal attention in congenitally deaf and hearing young adults. *Brain and Cognition*, 4(3), 313–327.
- Parasnis, I., Samar, V. J., & Berent, G. P. (2003). Deaf adults without Attention Deficit Hyperactivity Disorder display reduced perceptual sensitivity and elevated impulsivity on the Test of Variables of Attention (T.O.V.A.). *Journal of Speech, Language, and Hearing Research*, 46, 1166–1183.
- Pavani, F., & Bottari, D. (2012). Visual abilities in individuals with profound deafness: A critical review. In M. M. Murray & M. Wallace (Eds.), *Frontiers in the Neural Bases of Multisensory Processes* (pp. 423–447). Boca Raton, FL, USA: CRC Press.

- Pavani, F., & Röder, B. (2012). Crossmodal plasticity as a consequence of sensory loss: Insights from blindness and deafness. In B. E. Stein (Ed.), *The new handbook of multisensory processes* (pp. 737–760). Cambridge, MA: MIT.
- Posner, M. I. (1980). Orienting attention. *Quarterly Journal of Experimental Psychology*, 32, 3–25.
- Proksch, J., & Bavelier, D. (2002). Changes in the spatial distribution of visual attention after early deafness. *Journal of Cognitive Neuroscience*, 14, 687–701.
- Ptak, R. (2012). The frontoparietal attention network of the human brain: Action, saliency, and a priority map of the environment. *Neuroscientist*, 18(5), 502–515.
- Ptak, R., Camen, C., Morand, S., & Schneider, A. (2011). Early event-related cortical activity originating in the frontal eye fields and inferior parietal lobe predicts the occurrence of correct and error saccades. *Human Brain Mapping*, 32(3), 358–369.
- Rayner, K. (2009). The Thirty-Fifth Sir Frederick Bartlett Lecture: Eye movements and attention during reading, scene perception, and visual search. *Quarterly Journal of Experimental Psychology*, 62, 1457–1506.
- Scott, G. D., Karns, C. M., Dow, M. W., Stevens, C., & Neville, H. (2014). Enhanced peripheral visual processing in congenitally deaf humans is supported by multiple brain regions, including primary auditory cortex. *Frontiers in Human Neuroscience*, 8. <http://dx.doi.org/10.3389/fnhum.2014.00177>.
- Shiell, M. M., Champoux, F., & Zatorre, R. J. (2014). Reorganization of auditory cortex in early-deaf people: Functional connectivity and relationship to hearing aid use. *Journal of Cognitive Neuroscience*, 27(1), 150–163.
- Sladen, D. P., Tharpe, A. M., Ashmead, D. H., & Grantham, D. W. (2005). Visual attention in deaf and normal hearing adults: Effects of stimulus compatibility. *Journal of Speech, Language and Hearing Research*, 48, 1529–1537.
- Stivalet, P., Moreno, Y., Richard, J., Barraud, P. A., & Raphael, C. (1998). Differences in visual search tasks between congenitally deaf and normally hearing adults. *Cognitive Brain Research*, 6(3), 227–232.
- Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception & Psychophysics*, 51, 599–606.
- Theeuwes, J., Atchley, P., & Kramer, A. F. (2000). On the time course of top-down and bottom-up control of visual attention. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII: Control of cognitive performance* (pp. 105–124). Cambridge, MA: MIT Press.
- Townsend, J. T., & Ashby, F. G. (1983). *Stochastic modeling of elementary psychological processes*. Trumpington Street: Cambridge University Press.
- Vachon, P., Voss, P., Lassonde, M., Leroux, J. M., Mensour, P., Beaudoin, G., et al. (2013). Reorganization of the auditory, visual and multimodal areas in early deaf individuals. *Neuroscience*, 15(245), 50–60.
- van Zoest, W., & Donk, M. (2005). The effects of salience on saccadic target selection. *Visual Cognition*, 2(2), 353–375.
- van Zoest, W., & Donk, M. (2008). Goal-driven modulation as a function of time in saccadic target selection. *Quarterly Journal of Experimental Psychology*, 61(10), 1553–1572.
- van Zoest, W., Donk, M., & Theeuwes, J. (2004). The role of stimulus-driven and goal-driven control in saccadic visual selection. *Journal of Experimental Psychology: Human Perception and Performance*, 30(4), 746–759.
- van Zoest, W., Hunt, A. R., & Kingstone, A. (2010). Visual representations in cognition: It's about time. *Current Directions in Psychological Science*, 19(2), 116–120.
- Watanabe, K., Matsuda, T., Nishioka, T., & Namatame, M. (2011). Eye gaze during observation of static faces in deaf people. *PLoS ONE*, 6, e16919.
- Weichselgartner, E., & Sperling, G. (1987). Dynamics of automatic and controlled visual attention. *Science*, 238(4828), 778–780.