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The Role of Hearing in Central Cueing of Attention

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ABSTRACT

Our ability to be active agents in the world depends on our cognitive system to collect complex multisensory information, i.e. information coming from different senses, and integrate it appropriately. One fundamental topic of interest in the study of cognition is to understand the consequences of deafness on the organization of brain functions, specifically when one sensory modality is either lost or the information coming from that sensory modality is limited. In my work I used the spatial cueing paradigm to study how visual attention and selection is affected by diverse grades of congenital or acquired deafness in different life stages.

The goal of the first study was to validate an integrated approach of covert and overt orienting to study social and non-social cueing of attention in hearing adults. Specifically, I examined manual and oculomotor performance of hearing observers performing a peripheral discrimination task with uninformative social (gaze cue) and non-social cues (arrow cue). In Experiment 1 the discrimination task was easy and eye movements were not necessary, whereas in Experiment 2 they were instrumental in identifying the target. Validity effects on manual response time (RT) were similar for the two cues in Experiment 1 and in Experiment 2, though in the presence of eye movements, observers were overall slower to respond to the arrow cue compared to the gaze cue. Cue-direction had an effect on saccadic performance before the discrimination was presented and throughout the duration of the trial. Furthermore, I found evidence of a distinct impact of the type of cue on diverse oculomotor components. While saccade latencies were affected by whether the cue was social or not, saccade landing positions were not affected by cue-type. Critically, the manual validity effect was predicted by the landing position of the initial eye movement. This work suggests that the relationship between eye movements and attention is not straightforward. In hearing adults, in the presence of eye movements, saccade latency was related to the overall speed of manual response, while eye movements landing position was closely related to manual performance in response to the validity of the cues.

In the second study, I used the above-mentioned approach to investigate the impact of early profound deafness on the oculomotor control and orienting of attention to social and non-social cues. Previous research on covert orienting to the periphery suggests that early deaf adults are less sensitive to uninformative gaze cues, though were equally or more affected by non-social arrow cues. The aim of this second study was to investigate whether spontaneous eye movement behavior helps explain the reduced contribution of this social cue in deaf adults. Twenty-five deaf and twenty-five age-matched hearing observers took part in the experiment. In both groups, the cueing effect on RT was comparable for the gaze- and arrow-cue, although deaf observers responded significantly slower than hearing controls. While deaf and hearing observers responded equally to the cue presented in isolation, deaf participants relied significantly more on eye movements than hearing controls once the discrimination target was presented. Saccade landing position in the deaf group was affected by validity but not by cue type while latency was not modulated by these factors. Saccade landing position was also strongly related to the magnitude of the validity effect on RT, such that the greater the difference in saccade landing position between invalid and valid trials, the greater the difference in manual RT between invalid and valid trials. This work suggests that the contribution of overt selection in central cueing of attention is more prominent in deaf adults and determines the manual performance. The increase in eye movements and overall slower responses in deaf observers may act as an adaptive strategy to balance the need for accuracy in a context where vision and visual attention are used to monitor the surrounding environment in the absence of auditory input. This tendency to emphasize accuracy of response at the cost of responding more slowly seems to allow them to maintain the same level of cue-driven performance as their hearing peers.

In the third study I focused on partial hearing loss. Little is known on the consequences of pure presbycusis, which is usually associated with aging (Age-related Hearing Loss, ARHL). In this case, auditory information is still present, although linked to an amount of uncertainty regarding its usefulness. In this study I started to investigate the role of ARHL on cognition considering covert orienting of attention, selective attention and executive control. I compared older adults with and without mild to moderate presbycusis (26-60 dB) performing 1) a spatial cueing task with uninformative central cues (social vs. non-social cues), 2) a flanker task and 3) a neuropsychological assessment of attention. Notably, while hearing impaired individuals responded as equally fast as their normally hearing peers, they were characterized by reduced validity effects on spatial cueing of attention, though no additional group differences were found between the impact of social and non-social cues. Hearing impaired individuals also demonstrated diminished performance on the Montreal Cognitive Assessment (MoCA) and on tasks requiring divided attention and flexibility. Conversely, overall response times and flanker interference effects were comparable across groups. This work indicates that while response speed and response inhibition appear to be preserved following mild to moderate presbycusis, orienting of attention, divided attention and the ability to flexibly allocate attention, are more deteriorated in older adults with ARHL. These findings suggest that presbycusis might exacerbate the detrimental influences of aging on visual attention.

Taken together, the findings of my research project highlight the different role hearing loss may play at different life stages. On the one hand, congenital and early deafness seems to induce cognitive and behavioral compensations, which may encompass oculomotor behavior as well; these changes occur progressively during development and may reflect experience-dependent plasticity. On the other hand, late-life compensations in vision and visual attention in older adults with presbycusis may not take place or do not effectively reduce the negative impact of the auditory impairment. Rather, my data suggest that in this population a deficit in audition may consequently lead to a deficit in visual attention. Future lines of research can aim to better characterize other aspects of attention in the aging population with presbycusis, e.g. peripheral visual attention and the relationship between covert and overt attention. Finally, future research may also consider intervention through early diagnosis and treatment by means of hearing aids, which can be beneficial to cognitive functions and might delay or even prevent cognitive decline in this population, in which sensory compensation may not be sufficient.

CHAPTER 1

THEORETICAL BACKGROUND

1.1 Orienting of attention

Orienting of visual attention is indispensable for individuals to monitor and to select stimuli in the environment. In our eyes, the processing of the visual image is highest in the fovea, a small area in the central region of the retina, and declines rapidly from the fovea to peripheral regions of the retina. Therefore, the primary mechanism adopted to maintain visual processing optimal and to guarantee the highest visual acuity, is to move the eyes in the visual field in order to align the fovea with the object of interest and to *overtly* orient attention in space. The ocular fixation is often also the point where attention is, even though the relationship between the focus of attention and the position of the eyes is far more complex (see Kowler, 2011). Intuitively, we know that we can maintain fixation and the fovea in a portion of space and still attend to and process information from areas in the visual field not centered in the fovea. This phenomenon, the "*looking out of the corner of the eye*", was first empirically studied in the 19th century by Hermann von Helmholtz, who demonstrated by means of a tachistoscope how visual processing may be most efficient at the location of attentional focus rather than at ocular fixation (see Wright & Ward, 2008). The tachistoscope, a wooden box with two pinholes set one opposite the other, allowed Helmholtz to attend to a particular portion of space in his visual field while maintaining fixation on one pinhole. When a spark light briefly illuminated the box and the cardboard with letters printed on it, he found he could identify only the letters in the region where he decided in advance to concentrate his attention on. He suggested that attention can be independent from detectable eye and body movements, i.e. can be oriented *covertly*, and that the visual processing and identification of objects seem to depend on attentional focus more than on ocular focus. In the last decades, a wealth of empirical studies have better characterized the effects of covert attention on selection of stimuli and visual processing, showing how the attentional shift and focus is a mechanism promoting enhanced visual processing at locations different from ocular fixation (for a review, see Carrasco, 2011). The topic of visual attention is nowadays extremely vast. Yet, covert and overt orienting of attention have often been kept and studied separate. Although the exploration of these mechanisms in isolation has doubtless contributed to the understanding of attention in humans, the interplay between diverse components of attention, for example how covert and overt attention mechanisms interact together and which factors can influence this relationship, has received much less attention.

Most fundamental studies in visual selection assume intact abilities of the senses. While vision plays a crucial role in informing the cognitive system about the surrounding environment, the objects and events in a scene, its integration with another distal sense, hearing, is of great importance for an efficient exploration of the environment. In the lack or loss of auditory input, vision, visual attention and the interplay between attention orienting mechanisms are known to be impacted (e.g. Bavelier et al., 2000; Dye & Bavelier, 2010; Dye, 2016; Neville & Lawson, 1987; Quittner, Smith, Osberger, Mitchell, & Katz, 1994), but can adapt to some extent to serve specific roles, which are typical of the hearing sense. In my project I sought to better characterize covert and overt orienting of attention in cases of deafness. To understand to what extent visual attention is subject to change across the lifespan and how this depends on the type of hearing loss was an additional aim of my research project. In the next sections, I will give an overview of the current state of the art in the study of attentional orienting in hearing adults, together with a description of diverse forms of hearing loss and their implications on orienting of visual attention and on cognition.

1.1.1 Central and peripheral cues

The first fundamental distinction I will consider is between central and peripheral cueing of attention (Posner, 1980). As the name suggests, central cues are stimuli presented at the center of the visual field that enable to orient attention to another location in space; they differ from peripheral cues, which are displayed in a specific location in space away from the individual's point of fixation. In the last decades, studies on spatial attention have clearly demonstrated that individuals can orient attention in response to different types of spatial cues overtly and covertly, i.e. with or without detectable body movements. The Posner's location-cueing paradigm has been used to examine various features of covert attention, helping to make a first empirical distinction between reflexive orienting in response to peripheral cues and volitional orienting to centrally presented cues. In one of his first seminal studies, Posner (1978, 1980) presented participants with a fixation point followed by a central stimulus, which was an arrow pointing towards a location in space. Afterwards, participants were asked to detect a target displayed either on the left or on the right side of their visual field and reaction times (RTs) were recorded. Crucially, in most cases the central cue correctly indicated where the target would appear. The analysis of RTs revealed the presence of a cueing effect, i.e. shorter RTs when the cue validly pointed towards the upcoming target location and longer RTs when it did not. The effectiveness of the cue reached its peak when the time interval between the cue and the target (stimulus onset asynchrony, SOA) was 300 ms or more. Voluntary goal-driven processes were considered responsible for the observed behavioral effect, based on the fact that a central cue can exert its effect only when 1) there is enough time to understand its meaning and 2) when it is useful to achieve an intended goal (Jonides, 1981; Kröse & Julesz, 1989; Müller & Humphreys, 1991). This mechanism of orienting, also known as *endogenous attention*, differs substantially from a reflexive and stimulus-driven one, i.e. *exogenous orienting of attention*, which has been investigated using the abrupt onset of peripheral stimuli or illumination changes flashed close to the future target location (Posner, 1980). Reflexive orienting appeared to be short-lived, because it decayed when the SOA was longer than 150 ms. Peripheral cues tend to automatically capture attention and to be resistant to volitional control, in that performance was not affected by factors like validity of the cue, concurrent cognitive load or even awareness of the cue (Giordano, McElree, & Carrasco, 2009; Jonides, 1981; McCormick, 1997; Müller & Humphreys, 1991). Moreover, a characteristic inhibition of responses to targets appearing at cued or recently attended locations (inhibition of return, IOR) typically occurs to peripheral cues, where observers are slower to respond to the valid location that to the invalid location. IOR has been considered to be a marker of reflexive orienting (Posner & Cohen, 1984; Tipper, Grison, & Kessler, 2003; Wright & Richard, 1998, 2000). The different properties of the endogenous and exogenous orienting subsystems, both in terms of time course and of automaticity, seem to suggest that they developed for diverse purposes and they may rely on different brain structures. Even though there is no consensus yet on whether the two subsystems have shared neural networks or recruit distinctive brain areas or specific regions within the same network, the occipital, parietal and frontal cortex seem to be involved during endogenous and exogenous shifts of spatial attention. Several studies have pointed out enhanced activation of these brain areas in response to both peripheral and central cues that trigger diverse shifts of attention (Corbetta, Kincade, Ollinger, McAvoy, & Shulman, 2000; Hopfinger, Buonocore, & Mangun, 2000; Liu, Pestilli, & Carrasco, 2005; Peelen, Heslenfeld, & Theeuwes, 2004; for reviews see Carrasco, 2011; Corbetta & Shulman, 2002). Unlike cortical regions, subcortical structures in the brain such as the superior colliculus were thought only to mediate exogenous attention shifts, the IOR and eye movements both in primates and in humans, therefore adding converging evidence in favor of brain specialization for the exogenous mechanism of attentional orienting (Dorris, Klein, Everling, & Munoz, 2002; Henik, Rafal, & Rhodes, 1994; Rafal, Henik, & Smith, 1991; Schiller, True, & Conway, 1980). However, the superior colliculus has been more recently found to be active also during endogenous attentional orienting, thus questioning its recruitment only for exogenous shifts of attention (Lovejoy & Krauzlis, 2010; Meyberg, Sinn, Engbert, & Sommer, 2017; see Rolfs, 2009 for a review on microsaccades and shifts of spatial attention). In conclusion, exogenous and endogenous orienting have distinct properties, even though their underlying neural bases may be shared for the most part. Yet, in addition to the central voluntary cueing of attention and the automatic peripheral cueing, a third type of cueing with specific properties, effects on attention and diverse recruitment of brain regions has received considerable attention in the last two decades and has arisen a noteworthy debate in research: reflexive orienting to nonpredictive central cues.

1.1.2 Reflexive orienting to central cues

Recent studies have challenged dual-process theories of attention (Barrett, Tugade, & Engle, 2004; Corbetta & Shulman, 2002; Egeth & Yantis, 1997; Müller & Rabbitt, 1989), pointing in the direction of a re-discussion of the dichotomy of goal-driven (central cues) vs. stimulus-driven (peripheral cues) processes. Centrally presented social cues, like eye-gaze and gaze cues moving the eyes to the left or to the right, and non-social cues, like arrows pointing to the left or to the right, have been found to trigger automatic covert shifts of spatial attention. This automatic shifts occur when the cues are *nonpredictive*, i.e. 50% of times they correctly indicate the upcoming target location, or even *counterpredictive*, i.e. they indicate the non-target location most of times (Bayliss & Tipper, 2006; Driver et al., 1999; Friesen & Kingstone, 1998; Friesen, Ristic, & Kingstone, 2004; Hietanen, 1999; Hommel, Pratt, Colzato, & Godijn, 2001; Langton & Bruce, 1999; Ristic, Friesen, & Kingstone, 2002; Ristic, Wright, & Kingstone, 2007; Tipples, 2002). Interestingly, the cueing effect occurs rapidly, already at a SOA of 100 ms, it is long-lasting and it is not followed by the IOR. The automatic nature of this set of cues was first documented in a study of Friesen and Kingstone (1998) using a schematic face looking left, right or straight ahead, i.e. a gaze cue. Despite the fact that participants were fully aware that the cue was nonpredictive of target location, the gaze cue caused shifts of attention to gazed-at locations, which occurred irrespective of its validity. It was argued that this reflexive orienting effect was unique to biologically relevant stimuli. Later, nonpredictive non-social cues like arrows have been found to have similar effects on attentional orienting (Tipples, 2002). Altogether, these results have suggested that uninformative gaze and arrow cues may reflect another kind of reflexive process and that the dichotomy central vs. peripheral cues is not sufficient to account for all orienting mechanisms of visual attention (see e.g. Gibson & Kingstone, 2006 for another classification of cues based on the semantic of space). Some other evidence, however, have presented data against this view and support the idea that central cues like gazes and arrows produce endogenous shifts in attention (Gibson & Bryant, 2005; Vecera & Rizzo, 2004, 2006) and that frontal-lobe processes may be the ones involved in “social attention” and voluntary orienting of attention.

Although top-down modulations affect reflexive orienting to central symbolic cues to some extent (Ristic & Kingstone, 2005; Tipples, 2008), evidence in favor of purely automatic shifts to such cues are well-documented. The debate raised around similarities and differences of central nonpredictive cues and the link with spatial attention have led to different views. On the one hand, some have argued that cues like eye-gaze and arrows are both highly overlearned stimuli and therefore they produce similar effects on behavior (see Vecera & Rizzo, 2006; Wright & Ward, 2008). On the other hand, other authors consider gaze and arrow cues to be different. Direct comparisons between uninformative or counterpredictive gaze and arrow cues have highlighted gaze cues to be more reflexive and resistant to volition, suggesting that initial similarities in behavior do not represent an equivalence in the underlying mechanisms and neural architectures involved (Bayliss, Bartlett, Naughtin, & Kritikos, 2011; Friesen, Ristic, & Kingstone, 2004; Hietanen, Leppänen, Nummenmaa, & Astikainen, 2008; Hietanen, Nummenmaa, Nyman, Parkkola, & Hämäläinen, 2006). As a consequence, further investigations have sought to understand whether the gaze cue, as a biologically relevant stimulus for humans to develop social interaction and joint attention (Corkum & Moore, 1995), relies on diverse attention mechanisms compared to a non-biologically relevant cue, such as an arrow. Several experimental studies have directly compared the two cues both in terms of their behavioral effects and with respect to the possible neural mechanisms underlying this form of reflexive orienting (Carlin & Calder, 2013; Friesen, Moore, & Kingstone, 2005; Friesen et al., 2004; Hietanen, Leppänen, Nummenmaa, & Astikainen, 2008; Hietanen, Nummenmaa, Nyman, Parkkola, & Hämäläinen, 2006; Kingstone, Tipper, Ristic, & Ngan, 2004; Langdon & Smith, 2005; Ristic et al., 2002, 2007). The two nonpredictive cues share the fact of recruiting cortical brain networks for attention orienting and the effects of attention orienting on the processing of incoming information are similar (Hietanen et al., 2006; Ristic et al., 2002). Interestingly, though, neuropsychological data coming from a split-brain patient demonstrated a right-hemisphere involvement when directing attention to gaze-at location and a bilateral engagement in the case of an uninformative arrow cue (Kingstone, Friesen, & Gazzaniga, 2000; Ristic et al., 2002). Furthermore, Akiyama and colleagues (2006) tested a patient with focal right superior temporal gyrus (STG) damage, whose ability to use gaze cues as source of directional information was impaired, while the ability to orient attention to non-biological cues was intact. More recently, Hietanen and collaborators (2008) have suggested the existence of a ventral-fronto-parietal involuntary system for orienting in response to gazes and a dorsal-fronto-parietal, a more voluntary one, for arrows. While behavioral data often report similarities between nonpredictive social and non-social cues in the attentional orienting effects, neuropsychological data suggests that automatic orienting of attention in response to gaze cues and arrow cues is realized by –to some degree- different neural mechanisms.

The great majority of studies on attentional orienting I have presented so far have tested hypotheses on hearing individuals or brain-damaged patients. Yet, one can easily imagine that the loss of a sensory modality, such as hearing, can impact the way the world is perceived and the way people interact with it. In the case of visual attention, the lack of auditory input may lead to a broad and general reorganization of visual attentional mechanisms, or to specific modifications to compensate for the lack of auditory input, or to deficits and impairments in the remaining sensory modalities and therefore in perception and ultimately in cognition. In the next sections, I will illustrate the main characteristics of hearing loss and why it can be considered a model for studying cognition and brain plasticity.

1.2 Hearing loss

The World Health Organization (WHO) defines hearing loss on the basis of the hearing threshold in the better or both ears obtained by means of an audiometric test using pure tones at different frequencies, typically ranging from 250 to 8000 Hz. A person, whose average hearing threshold exceeds 25 dB, is said to suffer from hearing loss. The global estimates of disabling hearing loss in the world highlight a prevalence of 6.1% in the world's population, i.e. 466 million individuals living with hearing loss, and 93% of these are adults.

The severity of the hearing loss is classified into four categories:

1. Mild (hearing threshold between 26-40 dB);
2. Moderate (41-60 dB);
3. Severe (61-80 dB), also known as severe deafness;
4. Profound (> 81 dB), also known as profound deafness.

A further distinction that is necessary to be done is related to the onset of hearing loss. Hearing loss can be present since birth (congenital) or can be acquired very early in life because of specific diseases and medical interventions. Yet, progression into the old age is also characterized by a sequence of changes in cognitive functioning as well as progressive deterioration – to a various grade - of sensory modalities. For the purpose of this dissertation, I will refer to early bilateral profound deafness as the example of a congenital or prelingual condition of deafness and bilateral symmetrical pure presbycusis, also known as age-related hearing loss, as the form of acquired condition of deafness I have considered in my study on attentional orienting.

1.2.1 Early Profound Deafness

In Italy, 1.0 - 1.5 out of 1000 new-borns is diagnosed with deafness (“Ministero della Salute Italiano”, 2015). Sensorineural deficits in the auditory nerve are typically responsible for severe to profound deafness from birth. The aetiology of early deafness can be hereditary (~60%) or acquired by prenatal or postnatal infections, encephalitis, rubella infection, anoxia during birth, trauma or due to ototoxic drugs (“Ospedale Niguarda”, 2015). When it is not associated with other pathologies and illnesses, deafness prevents children from being exposed to any spoken languages and therefore represents a sever risk for delay of even lack of acquisition and development of spoken languages. Nonetheless, deafness does not hamper acquisition of a first language that relies on vision. Sign languages are visual languages that are used all over the world by deaf communities and the individuals who know and use such visual languages are called signers. Decades of linguistic as well as experimental research has demonstrated that sign languages share the same core characteristics of spoken languages and are not merely a collection of gestures (see for example Caselli & Volterra, 1990; Emmorey, 2000; Emmorey et al., 2002; Stokoe, 1960).

Although sign language represents a natural and valid communication strategy in this population, cochlear implants and hearing aids are the principal way to regain access to auditory stimuli. However, the practical benefit of these technologies is subject to high variability across individuals. In fact, not all infants that are born deaf or become deaf early in their life can receive a cochlear implant (CI) or can successfully perceive speech and normally develop language thanks to this surgical intervention (Geers, Nicholas, & Moog, 2007; Miyamoto, Houston, Kirk, Perdew, & Svirsky, 2003). Spared auditory nerve functions are fundamental for auditory restoration using a cochlear implant, because the electronic device transforms auditory stimuli into electrical pulses that are delivered directly on the nerve fibers in the cochlea. In addition, young age plays an important role in the success of the intervention (Nikolopoulos, O'Donoghue, & Archbold, 1999; Sharma, Dorman, & Spahr, 2002; Tomblin, Barker, Spencer, Zhang, & Gantz, 2005). Alternatively, hearing aids are less invasive devices that can help improve auditory processing and speech intelligibility by means of digital signal reconstructions, but also in this case the quality of the final result depends on the gravity of deafness and on a personalized configuration called “fitting” that is done by audiologists (Pichora-Fuller & Singh, 2006). It is not rare to see deaf adults without any hearing aids or deaf adults that have got rid of a previously installed cochlear implant. Auditory experience for these individuals may have resulted in being very noisy, confusing and unintelligible, particularly with respect to speech. In addition, it is known that the brain reconstructs spatial locations of sounds in the environment thanks to binaural indices, e.g. using time- or intensity-differences of incoming sounds in both ears (Grothe, Pecka, & McAlpine, 2010). Having only a unilateral cochlear implant or hearing aid is not sufficient to enable deaf individuals to localize sounds in space and this turns to be another limitation of these devices (Tyler, Dunn, Witt, & Noble, 2007; Verschuur, Lutman, Ramsden, Greenham, & O'Driscoll, 2005). Sound localization helps localizing sound sources in space and plays an important role in cueing both auditory attention and visual attention to visual stimuli associated with attended sounds, thus facilitating visual processing of these stimuli (e.g. Hillyard, Störmer, Feng, Martinez, & McDonald, 2016).

Research on deafness has shed light into reorganizations occurring in other sensory modalities that enable deaf people to control the surrounding environment and localize visual stimuli in an effective way, despite the lack of auditory input and sound localization. In the case of severe-to-profound deafness, research has empirically confirmed what in the past was anecdotal, for example that deaf adults seem to show enhanced visual capacities in the periphery of the visual field (see for example Bavelier et al., 2000; Dye & Bavelier, 2010; Dye, Baril, & Bavelier, 2007; Neville & Lawson, 1987). Although deaf adults seem to shift their attention very rapidly to the periphery, this does not automatically imply that deafness results in an uncontrolled prioritization of events that occur in the corner of the visual field. Research work on visual selection in this population has highlighted the presence of reflexive mechanisms of orienting, but also an increased control of eye movements, depending on the task (Bavelier, Dye, & Hauser, 2006; Bottari, Valsecchi, & Pavani, 2012; Heimler et al., 2015a). In this sense, plastic reorganizations following early deafness seem to lead to a flexible management of attentional resources depending on the situation, as I will illustrate in details in Chapter 3.

1.2.2 Age-related Hearing loss

Acquired hearing loss may occur after long-term exposure to excessive noise and loud sounds, ear infections, head or ear injuries and trauma, and aging (WHO). In the course of life, one of the major factors driving structural modifications and changes in cognition is aging. Western societies have experienced a boost in life expectancy over the last century because of increasing ameliorations of healthcare and socio-economic standards. Sensory functioning in vision and hearing can be impaired in older adults to various degrees, but decline affects also visual and auditory perception (Monge & Madden, 2016; Tun, McCoy, & Wingfield, 2009). Therefore, research has started to get a closer look at age-related changes in cognition, especially to tease apart natural and healthy from pathological modifications, in an attempt to recognize cognitive decline and neurodegenerations in the early stages.

Interestingly, recent hypotheses have suggested an association between age-related hearing loss, also known as pure presbycusis, and cognitive decline based on several facts that the two have in common. With increasing level of presbycusis, the incidence of Alzheimer's disease (AD) tends to increase (Dawes et al., 2015; Hubbard, Mamo, & Hopper, 2018; Lin, Ferrucci, et al., 2011; Lin, Metter, et al., 2011). Furthermore, presbycusis at later stages of life negatively affects quality of life and social interaction beyond the mere sensory impairment, as the increasing difficulty and associated fatigue in speech comprehension and in understanding speech in noise often results in social isolation. Older adults with presbycusis can still achieve a sufficient level of speech comprehension, but only at the cost of increased use of executive functions and working memory, which in turn tend to decline as well in this population (Hubbard et al., 2018; Mishra, Stenfelt, Lunner, Rönnberg, & Rudner, 2014; Rönnberg et al., 2016). Interestingly, mild cognitive impairment (MCI), which is a significant risk factor for AD, is also associated with social withdrawal and impairments in speech comprehension (Dawes et al., 2015; Jalaei et al., 2019; Yu, Lam, & Lee, 2016). Furthermore, deficits in executive functions and working memory are considered predictors of mild cognitive impairment and increased risk of cognitive decline in cognitively normal older adults (Farias et al., 2017). It remains an open question whether cognitive impairments associated with presbycusis may be potentially reduced by means of auditory-function treatment options, including hearing aids and cochlear implants. Hearing restoration interventions have led to increased interest and expectations for the potential positive consequences on cognitive functions and mood disorders among older adults (see for example Castiglione et al., 2016; Dawes et al., 2015; Di Nardo, Anzivino, Giannantonio, Schinaia, & Paludetti, 2014; Gieseler, Tahden, Thiel, & Colonius, 2018; Hubbard et al., 2018; Mosnier et al., 2015; Rudner & Lunner, 2013).

In conclusion, the commonalities between pure presbycusis and cognitive decline among older adults seem to indicate that at least an overlap is likely. Nevertheless, further research is needed to determine the direction of association, i.e. whether there is a direct causal relationship between pure presbycusis and cognitive deterioration. In addition, repercussions of presbycusis on other non-linguistic and memory domains of cognition, such as attention, remains largely unexplored. Hence, in Chapter 4 I will present my empirical investigation of visual attention abilities in the presence of presbycusis in older adults.

1.3 Deficit or compensation?

Attention is a multi-component cognitive domain and it involves a family of cognitive processes. In the previous sections I have maintained the main focus on the examination of relevant aspects of attentional orienting in the visual modality, underlying distinctions emerged mainly from the last decades of research. Yet, the main goal of my research project was to further address some critical aspects of the possible reorganizations exerted by deafness on visual attention and orienting of attention. For this reason I have illustrated key features of the two forms of hearing loss I have considered in my research work; early profound deafness and pure presbycusis are qualitatively very different, but they both provide a unique opportunity to explore the consequences of the absence or reduction of the auditory modality on cognition across the lifespan. Specifically, studying the effects of hearing loss at different life stages has the potential to shed light on the mechanism considered responsible for changes in the brain following new or altered experiences, i.e. plasticity.

Two opposite views have characterized the interpretations of behavioral changes following early profound deafness. The first view, i.e. the *deficit hypothesis,* states that the lack of the one sense would negatively influence the development of the remaining senses and thus translates into deficits in the other modalities (Pavani & Bottari, 2012; Radell & Gottlieb, 1992; Turkewitz & Kenny, 1982). Some reports have converged in this direction (e.g., Quittner, Leibach, & Marciel, 2004; Quittner, Smith, Osberger, Mitchell, & Katz, 1994; Parasnis, Samar, & Berent, 2003), highlighting deficits in visual attention in deaf children. However, the observation that deaf adults have comparable performance in measures of sensory thresholds (e.g. Bross & Sauerwein, 1980; Finney & Dobkins, 2001) or even enhanced abilities in specific aspects of visual attention does not speak in favor of a deficit view. Instead, according to a *compensation hypothesis*, deafness would turn into a greater reliance on the remaining senses, which would result into an enhancement of the other modalities (Grafman, 2001; Neville, 1990). This latter proposal is tightly linked with the concept of crossmodal plasticity. Following the loss of input from one sensory modality, brain regions specialized in processing information from that deprived sensory modality reorganize to subserve the analysis of intact sensory modalities, leading to altered, often enhanced, performance in remaining senses. An increasing number of studies have reported modifications in vision and touch following early deafness that appear to serve an adaptive role in everyday living to effectively monitor the environment and interact with the others (Bavelier et al., 2000; Bavelier et al., 2006; Bottari, Nava, Ley, & Pavani, 2010; Bottari et al., 2012; Dye & Bavelier, 2010; Dye et al., 2007; Heimler, van Zoest, Baruffaldi, Donk, et al., 2015a; Heimler, van Zoest, Baruffaldi, Rinaldi, et al., 2015b; Pavani, Venturini, Baruffaldi, Caselli, & Zoest, 2019; Proksch & Bavelier, 2002). The functional and anatomical reorganization taking place within the visual modality (e.g. Bavelier et al., 2006; Benetti et al., 2017; Dye, Hauser, & Bavelier, 2008; Mitchell & Maslin, 2007) has received considerable attention, especially because it has been empirically demonstrated that not all aspects of visual processing are enhanced in profound deaf individuals. In particular, key findings in the literature of crossmodal plasticity in profound deafness highlight faster reaction times when detecting or discriminating single peripheral visual targets (e.g., Bavelier et al., 2000; Bavelier et al., 2001; Bosworth & Dobkins, 2002; Colmenero, Catena, Fuentes, & Ramos, 2004; Lore & Song, 1991; Neville & Lawson, 1987) and orienting of covert attention towards periphery of the visual field when concurrent central and peripheral targets compete for attentional resources (Chen, Zhang, & Zhou, 2006; Dye, 2016; Proksch & Bavelier, 2002; Sladen, Tharpe, Ashmead, Grantham, & Chun, 2005) and enhanced efficiency or control in the processing of faces and social cues (Emmorey, Thompson, & Colvin, 2009; Heimler, van Zoest, Baruffaldi, Rinaldi, et al., 2015b; Pavani et al., 2019; Watanabe, Matsuda, Nishioka, & Namatame, 2011; Bonmassar, Pavani, Di Renzo, Caselli & van Zoest, submitted). Notably, rather than showing an enhancement of attentional resources in both central and peripheral locations, what is peculiar of profound deafness is the redistribution of attentional resources towards periphery at costs of worse processing in central locations, when both central and peripheral stimuli are presented (see Dye, 2016). Enhanced performance at the periphery of the visual field is in line with the idea that the auditory system provides relevant information about the events occurring outside the field of view. Early deafness may boost the recalibration of vision and visual processing to promote rapid detection of events outside the fovea. Importantly, this phenomenon does not seem to be present since birth, as several studies on deaf children failed to show comparable redistributions of attentional resources (e.g. Codina, Buckley, Port, & Pascalis, 2011; Dye & Bavelier, 2010; Dye & Hauser, 2014; Pavani et al., 2019). It is thought that crossmodal plasticity follows a developmental trajectory and results from both the progressive maturation of the visual system, involving the gradual increase of attentional control from childhood to adulthood, and other concurrent experiences, e.g. learning of a sign language or speechreading (Bosworth, Petrich, & Dobkins, 2013; Lieberman, Hatrak, & Mayberry, 2014; McCullough & Emmorey, 2009). Furthermore, the reorganization of visual processing does not appear to be limited to covert attention; it may encompass overt oculomotor control as well, showing evidence for both more reflexively driven selection as well as evidence for improved control as a consequence of delayed eye movements (Bottari et al., 2012; Heimler, van Zoest, Baruffaldi, Donk, et al., 2015a; Prasad, Patil, & Mishra, 2015). Altogether, these findings seem to be the sign of a context dependent enhanced flexibility of the oculomotor system in deaf observers. However, the two orienting mechanisms of covert and overt selection have often been studied separate, although they strongly interact in everyday life (Wright & Ward, 2008). Consequently, an aspect worth investigating is the interplay between covert attention and overt selection in this population, which remains poorly examined and understood.

To summarize, changes in the domain of visual attention and orienting resulting from early profound deafness are highly specific and do not broadly encompass all aspects of attention. In fact, they appear to be the result of a powerful plastic re-adaptation of the brain to face the lack of an important sensory modality like audition. Yet, one could ask whether effects of crossmodal plasticity remain possible and can be observed irrespective of the moment in life in which a loss or an attenuation of auditory input occurs. Aging is characterized by alterations in cognitive functioning and by progressive deterioration of sensory modalities. The effects of acquired deafness at later stages in life may impact cognition and may lead to modifications in orienting of visual attention that are very different from early onset deafness. However, the consequences of later acquired deafness are still largely unknown. Generally speaking, the association between presbycusis and cognitive decline has received considerable attention in recent years, thus implicitly emphasizing that deterioration, rather than adaptive reorganization of the brain or sensory compensation, may be triggered by or follow pure presbycusis (Baltes & Lindenberger, 1997; Dawes et al., 2015; Fortunato et al., 2016; Lin, Metter, et al., 2011; Lin et al., 2013; Lindenberger & Baltes, 1994; Loughrey, Kelly, Kelley, Brennan, & Lawlor, 2018; Strawbridge, Wallhagen, Shema, & Kaplan, 2000; Tun et al., 2009; however see Wettstein, Wahl, & Heyl, 2018 for recent evidence supporting sensory compensation). The four most influential hypotheses that seek to elucidate the conjunction of sensory and cognitive decline focus predominantly on the cascade of negative consequences on cognition in the presence of presbycusis. First, according to the *cognitive load on perception hypothesis* (Lindenberger & Baltes, 1994), poor cognition is the factor driving perceptual decline by significantly and irremediably depleting cognitive resources at disposal. However, evidence in favor of this hypothesis is limited and probably due to confounding factors like administration of test requiring intact hearing capacity (see Wayne & Johnsrude, 2015). Second, the *common cause hypothesis* posits that age-related loss in the anatomical and functional integrity of the brain due to a third factor, like cerebrovascular disease, neuropathology etc., is responsible for both cognitive and sensory decline (Baltes & Lindenberger, 1997). This proposal stems from the observation that cognitive decline tends to affect multiple domains of cognition and perception at the same time. Therefore, a common neurodegenerative etiology could account for the variety of impairments, including deficits in visual perception, olfaction, speech perception and executive functions, reported in different studies (e.g. Devanand et al., 2010; Humes, Busey, Craig, & Kewley-Port, 2013; Lin & Ferrucci, 2012; Shargorodsky, Curhan, Eavey, & Curhan, 2010; for reviews see Roberts & Allen, 2016; Wayne & Johnsrude, 2015). Third, the *sensory-deprivation hypothesis* claims that sensory impairment has a direct impact on cognition. Attenuation of senses results in lack of sensory input and thus in insufficient cognitive stimulation, which ultimately triggers cognitive decline (Humes et al., 2013; Lin et al., 2013; Lindenberger & Baltes, 1994; Pichora-Fuller, 2003). Moreover, it suggests that neuroplastic changes hamper general cognition in favor of processes aiding speech perception; documented cortical changes such as decrement in gray matter density and decreased cortical activations in auditory regions are likely to reflect maladaptive reorganizations following reduced sensory input (e.g. Lin et al., 2014; Meredith, Keniston, & Allman, 2012; Peelle, Troiani, Grossman, & Wingfield, 2011). Finally, the *information degradation hypothesis* states that sensory deficits like presbycusis may be compensated to some extent by increased reliance on cognitive resources like working memory and executive processing. The re-allocation of those resources to perception would reduce their availability for other tasks and processes, leading to poor cognitive performance (Mishra, Lunner, Stenfelt, Rönnberg, & Rudner, 2013; Mishra et al., 2014; Monge & Madden, 2016; Pichora-Fuller, 2003; Rönnberg et al., 2016; Rudner & Lunner, 2013; Schneider & Pichora-Fuller, 2000; Strawbridge et al., 2000). Interestingly, this latter hypothesis introduces the possibility that cognitive impairments may be reversible, if the cognitive efforts required to guarantee perceptual analysis from limited perceptual input and consequent fatigue were somehow limited.

It remains unclear to what extent cognitive decline occurs as a function of the increased cognitive demands in perception in acquired deafness, or occurs irrespectively of these changes. However, the recent observation that cognition can have a compensatory role in adapting to impaired perception suggests that compensatory cognitive processes and crossmodal plasticity may take place in the aging brain (Roberts & Allen, 2016; Schulte et al., 2011; Wettstein et al., 2018). In addition, cognition in older adults can improve via optimization of resources as shown by series of studies on the effects of cognitive training on older adults without specific diseases (Gieseler et al., 2018; Kelly et al., 2014; Morrison & Chein, 2011; O'Brien et al., 2013; Reijnders, van Heugten, & van Boxtel, 2013; Rienäcker, Jacobs, Van Heugten, & Van Gerven, 2018). Taken together, these considerations may support the notion that plasticity can be present at later stages of life; in the case of presbycusis, and similar to early profound deafness, the loss may lead to adaptive and specific reorganizations of visual attention that may be evident in behavior. Importantly, the possibility of late-life compensations via visual attention following age-related presbycusis has not been directly examined yet. In my research project, I have sought to examine whether age-related presbycusis has specific implications in attentional orienting or whether it leads to a more general deficit in visual attention.

To conclude, the aim of my research project was threefold: 1) to validate an integrated approach to study the interplay between covert and overt orienting of attention to central social and non-social cues in hearing adults (Chapter 2) and 2) apply this approach to the study of oculomotor control and its relationship with covert attention to central cues in early profound deaf adults (Chapter 3). Finally, 3) I investigated whether and how visual attention and attentional control reorganizes as a consequence of presbycusis (Chapter 4).

CHAPTER 2

CENTRAL CUEING IN HEARING ADULTS

The following chapter has been published in form of peer-reviewed article:

Bonmassar, C., Pavani, F., & van Zoest, W. (2019). The role of eye movements in manual responses to social and non-social cues. *Attention, Perception & Psychophysics,* Volume 81, Issue 5, pp 1236–1252, DOI: 10.3758/s13414-019-01669-9

2.1 Introduction

Orienting spatial attention in response to head turning and eyes moving is part and parcel of living in a society. Humans are very sensitive to the processing of eye-gaze, a preference that is thought to be innate and find its roots in evolution (see for example Hood, Willen, & Driver, 1998). In the course of life, we learn to orient attention also to more abstract cues like arrows, given that they also convey useful spatial information. So, we are able to shift our attention also according to directions conveyed through signs, e.g. when looking for the right exit from the motorway. Eye-gaze or arrows are known as central cues, i.e. stimuli that are presented at the center of the visual field and that enable to orient attention to another location in space; they differ from peripheral cues, which can capture attention to their location because of an abrupt onset of by means of illumination changes (Posner, 1980).

A large number of studies have been conducted to understand the characteristics of attention orienting to central cues, mainly focusing on the covert component of it, i.e. the orienting of visuospatial attention without observable eye and body movements (Driver et al., 1999; Friesen & Kingstone, 1998; Posner, 1978, 1980). The aim of the present work is to investigate the role of overt shifts of attention in the processing of central arrow and gaze cues.

2.1.1 Covert responses to central cues

Attention orienting to central cues has been extensively investigated by means of the spatial cueing paradigm (Posner, 1978, 1980). Typically, participants are presented with a central arrow pointing to the left or to the right and are asked to respond to a target appearing at previously cued- or uncued-locations. Manual RTs are faster for targets appearing at cued locations relative to those appearing at uncued locations. Crucially, in a high proportion of trials the central cue correctly indicated where the target would appear, creating an incentive for observers to pay attention to the direction of the cue (Jonides, 1981; Kröse & Julesz, 1989; Müller & Humphreys, 1991). It has been argued that voluntary goal-driven processes are primarily responsible for the observed behavioral effect. However, more recent studies have challenged the idea that central cues instigate goal-driven orienting of attention only (Corbetta & Shulman, 2002; Egeth & Yantis, 1997; Müller & Rabbitt, 1989). Centrally presented arrow cues have been found to trigger automatic covert shifts of spatial attention also when they are nonpredictive, or even counter-predictive of the upcoming target location (Friesen et al., 2004; Hommel et al., 2001; Ristic et al., 2002; Tipples, 2002).

The discovery that central arrow cues are capable of directing attention automatically was in part motivated by the findings from the gaze-cue literature (e.g. Bayliss & Tipper, 2006; Driver et al., 1999; Friesen & Kingstone, 1998; Friesen, Ristic, & Kingstone, 2004; Hietanen, 1999; Hommel, Pratt, Colzato, & Godijn, 2001; Langton & Bruce, 1999; Ristic, Friesen, & Kingstone, 2002; Ristic, Wright, & Kingstone, 2007; Ristic & Kingstone, 2009). In the work of Friesen and Kingstone (1998) participants performed a spatial cueing task with a central schematic face, whose gaze direction was nonpredictive of target location. Responses were facilitated by a valid gaze cue compared to a neutral or an invalid one. The attentional benefit was observed for short cue-target stimulus onset asynchronies (SOAs), adding evidence in favor of a reflexive orienting in response to the eye-gaze. However, the aforementioned studies focused on aspects related to covert attention to nonpredictive central cues. Covert measures such as manual reaction times (RTs) depend on inferences regarding the deployment of attention in space. For example, with respect to RTs, the assumption is that attention shifts in line with the direction indicated by the gaze or arrow cue. However, only once the manual response is triggered it becomes evident how visual information processing was affected by the direction of the central cues. In contrast to covert mechanisms, which give little information about the underlying temporal dynamics, overt mechanisms of orienting are associated with detectable eye and body movements (Frischen, Bayliss, & Tipper, 2007; Wright & Ward, 2008) and provide a window into the ongoing and underlying selection processes. For example, in the central cueing paradigm, concurrent recording of eye movements can yield a measure of eye position at each millisecond along the way, from the moment the cue is presented until the final manual response. In this way, eye movements can provide a way to investigate how overt processing contributes to the manual response to nonpredictive central cues.

2.1.2 Overt responses to central cues

There are a number of studies that have investigated eye movements in central gaze-cueing (see for example Dalmaso et al., 2015; Kuhn & Benson, 2007; Kuhn et al., 2009; Kuhn, Tatler, & Cole, 2009; Kuhn et al., 2011; Kuhn & Kingstone, 2009; Mansfield, Farroni, & Johnson, 2003; Ricciardelli, Bricolo, Aglioti, & Chelazzi, 2002). However, in the majority of these studies participants were explicitly instructed to make an eye movement to the target. For example, Kuhn and Kingstone (2009) explored the effect of nonpredictive and counter-predictive gaze and arrow cues on the planning and execution of voluntary saccades. The color of the fixation point indicated the saccadic target location. For instance, when the fixation point changed to green, observers were instructed to make a saccade to the right target location and this location could be either congruent or incongruent with the central arrow or gaze cue. The dependent measures included saccadic reaction time to the peripheral target and directional eye-movement errors, where saccadic responses were considered correct if they were directed in the general direction of the target (i.e., to the left or right side of screen). The analysis of latency on correct saccades revealed that congruent trials were faster than incongruent trials, both when the gaze cue was nonpredictive and counter-predictive of saccadic target direction. Moreover, error saccades occurred especially on incongruent trials and were characterized by even shorter latencies compared to correct saccades, supporting the idea that erroneous gaze-following occurred automatically. These findings add further evidence in favor of reflexive orienting to gaze cues, and extend findings that originated from the literature on covert orienting of attention. In addition, Kuhn & Kingstone (2009) directly compared counter-predictive gaze and arrow cues and showed that saccade latencies and errors were comparable across gaze and arrow cues. This finding conflicts with previous research on covert attention with counter-predictive cues, that found evidence for covert reflexive orienting in response to counter-predictive gaze cues, but not arrow cues (Friesen et. al, 2004; however see Tipples, 2008).

While the work of Kuhn and Kingstone (2009) clearly reveals that overt selection is affected by nonpredictive gaze cues or even counter-predictive gaze and arrow cues, as manual reaction times were not measured in this work, it remains unclear to what extent saccadic behavior influences or potentially even guides overt manual responses. Moreover, in the work of Kuhn and colleagues the measure of overt selection in terms of landing position was very general (i.e. to the left or right) and involved saccadic responses given after the target and distractor were presented. Thus, it is unclear how more spontaneous overt selection - without explicit motivation to make an eye movement to the target - is affected by the presentation of the cue. The present work will measure saccadic position throughout the duration of the trial to see how the various events, i.e., presentation of the cue and presentation of the target, directly influence dynamic eye movement behavior. Thus, rather than explicitly instructing observers to make eye movements to a given target, or at a certain point in time, I measured natural variability in oculomotor performance throughout the trial to find out how various oculomotor measures relate to attentional performance.

The goal of the present study is two-fold. First, to investigate the role of spontaneous eye movements in central cueing and to understand whether and how the contingency between eye movements and attention modulates gaze and arrow cue processing. Second, because I presented participants with both the arrow- and the gaze cue, I could investigate potential differences in the processing of uninformative gaze and arrow cues. Eye movements, because they are typically elicited faster than manual responses, represent a more direct measure to probe automatic processing. If gaze cues cause more reflexive orienting than arrow cues, I expect to see a greater influence of gaze cues on eye movement performance compared to arrow cues. For the gaze cue I used an avatar face stimulus, while the arrow was a simple line drawing. Though my stimuli are vastly different in terms of complexity, validity was manipulated orthogonal to stimulus-complexity and not confounded.

I conducted two experiments. Experiment 1 was more exploratory, whereas Experiment 2 was used to confirm the main findings on Experiment 1. In Experiment 1, the discrimination task was relatively easy and could be completed maintaining fixation at the center of the screen. While overt movements were neither required nor necessary to perform the task, making supporting eye movements was not prohibited. Experiment 1 was presented as a typical standard covert attention cueing task and with regards to eye movements, at the beginning of each main part of the experiment and after recalibrations, I instructed participants to try and maintain fixation throughout the experiment and respond as fast and accurate as possible to the target. However, fixation was not enforced and no feedback was provided on eye movement behavior. Thus, even though I told observers to maintain fixation, I expected to observe natural variability between trials and across participants in the ability to do so. In a second experiment, the discrimination task was made more difficult, such that eye movements were more critical to performance compared to Experiment 1. The instructions given to participants in Experiment 2 were identical to that of Experiment 1 to ensure that the initial motivation and strategies in terms of fixation were similar across experiments. If eye movements are instrumental in the manual cueing effect, I expect to find a relationship between eye movement performance and RT. Moreover, I predicted that this relationship should be stronger in Experiment 2 where eye movements were critical to performance compared to Experiment 1, where eye movements were not.

Note, that I did not force fixation. Designs with forced viewing conditions are likely to lead to design-specific strategies which would confound my measure of interest, the natural eye movement behavior. While there are studies that directly compared covert with overt attention independently, the strength of my work is that I studied these concurrently, rather than separately. The present work combines covert and overt measures, i.e. manual RT and eye-movement components, to see how eye movements relate and potentially help to explain covert attentional cueing.

2.2 Experiment 1

2.2.1 Methods

Participants

Twenty young adults aged 19-26 (M = 22.4 years old; SD = 3.5; females = 10; 2 left-handed) were recruited from the local student population of the University of Trento and were tested in the CIMeC psychophysics laboratories. All participants had normal or corrected-to normal vision. This research was conducted according to the principles expressed in the Declaration of Helsinki, and informed consent of each participant was obtained. The study was approved by the Ethical Committee of the University of Trento (Ethical approval code: 2016-029) and all participants received either a reimbursement of 7 €/hour or University credits for their participation. Though my methodological approach to the question is novel, based on previous work that has looked at covert central cueing with similar stimuli (Blair, Capozzi, & Ristic, 2017; Heimler et al., 2015b, experiment 2; Tipples, 2002) I calculated an estimation of the effect size. Main effects of cue validity and cue-target stimulus onset asynchrony reported in Blair et al. (2017) had effect sizes respectively of $\eta^2_p = .53$ and $\eta^2_p = .63$. To obtain a desired statistical power of .90 for these main effects corrected for publication bias (Anderson, Kelley, & Maxwell, 2017) and with an alpha value of .05, a minimum sample size of twelve individuals was required. Hence, my sample of twenty observers was appropriate for testing these effects.

Stimuli

The experiment was run on a 23-inch Asus VG 236 LCD monitor (100 Hz; resolution 1920x1080 pixels) that was set up with a viewing distance of 60 cm. Stimulus presentation was controlled by an AMD Radeon Graphics FirePro V4900 graphics card. Luminance values were set using a Minolta CS-100A luminance meter. The background was presented in black with a luminance of 0.17 cd/m^2 (RGB: 0, 0, 0). A fixation dot was presented at the center of the screen at the beginning of each trial and served to perform the drift correction. The target, distractor and arrow stimuli were light gray (RGB: 198, 197, 203) with a luminance of 47 cd/m^2.

Target and distractor consisted of two 90° rotated squares (width 1° of visual angle) and were presented at an eccentricity of 11° from the center of the screen. The distractor was always a 90° rotated whole square, whereas the target could have the bottom or the top part missing; the missing part was a triangle, whose height was one fourth of the total height of the square (see Figure 1, panel B). The spatial cues consisted of a face and an arrow presented centrally (dimensions of the two stimuli were respectively 7.2°x 11.5° and 2.7° x 1.3° width x height). The face was taken from a face database (Oosterhof & Todorov, 2008). The two directional gaze images (gaze left and right) were created from the straight-ahead gaze (see Figure 1, panel A) using Photoshop. The non-social cue was first a horizontal line with two arrowheads that could point to the left or right side. All stimuli except the face stimulus were created using Opensesame (Mathôt, Schreij, & Theeuwes, 2012) and the experiment itself was run using Opensesame, together with the PyGaze library (Dalmaijer, Mathôt, & Van der Stigchel, 2014) and the Psychopy backend (Peirce, 2007, 2009) to synchronize the PC with the eye-tracker host-PC (Opensesame version 3.1.3; Pygaze 0.6.0a21).

Procedure and Design

Participants were seated on an adjustable chair in front of the monitor in a dimly lit room. Head movements were controlled by means of a chinrest. Participants' gaze was tracked throughout the experiment using a SR Research Ltd., Eyelink 1000 PLUS, consisting of an eye-tracking system connected to a laptop (host-PC). It collected monocular gaze position at a sampling rate of 1000 Hz from the left eye. A 5-points-grid calibration routine was completed the beginning of each experimental condition and at the end of the third block in each experimental condition, for both gaze and arrow cue conditions. Therefore, a total number of 4 calibration routines were executed throughout the experiment; additional calibrations were added when necessary (e.g. poor recording due to glasses or contact lenses reflection).

Participants were told to fixate the central fixation dot at the beginning of each trial, to try and maintain fixation and to ignore the cues because uninformative. After the drift correction procedure, to make sure that participants' gaze was at the center of the screen, the trial began. Depending on the cue-type condition, which was presented in different blocks, a face with straight-ahead gaze or a horizontal line was shown for 1000 ms. This neutral stimulus was followed by the presentation of the directional cue and it consisted either of a face looking to the left or to the right side or an arrow pointing to the left or right side. Crucially, cue direction for both the gaze-cue and arrow-cue was not predictive of target location. On half of the trials the target appeared on the side indicated by the cue (valid trials), and in the remaining half of trials the target appeared on the opposite side (invalid trials). Two stimulus onset asynchronies (SOA 250 ms or 750 ms) between the cue and target appearance were used in a randomized fashion to detect any changes in the cueing effects as a function of time (Friesen & Kingstone, 1998; Heimler, van Zoest, Baruffaldi, Rinaldi, et al., 2015b; Ristic et al., 2002). The task of the participants was to discriminate whether the target was cut on the top or on the bottom part, while keeping fixation at the center of the screen. Participants responded by pressing the 'up' or 'down' arrow buttons on the computer keyboard with the index and middle fingers of their dominant hand. Participants were instructed to respond as fast and accurate as possible, indicating whether the target missed the top or the bottom part, independently of the side of the screen in which the target appeared (see Figure 1, panel A). The experiment comprised 16 practice trials and 160 experimental trials divided in 5 blocks for each condition (gaze vs. arrow). Hence, participants completed a total number of 32 practice + 320 experimental trials. Cue-type condition was counterbalanced across participants. At the end of each block participants received feedback on the average response times (RTs) and on the percentage of correct responses and were free to take a break. Written instructions and visual sketches of the trial sequence were shown on the screen before starting the practice and reiterated before starting each experimental condition. As my aim was to investigate whether eye movements would spontaneously occur in this typical covert attention experiment, participants did not receive any feedback when they failed to maintain fixation and no additional feedback related to eye movement performance was provided.

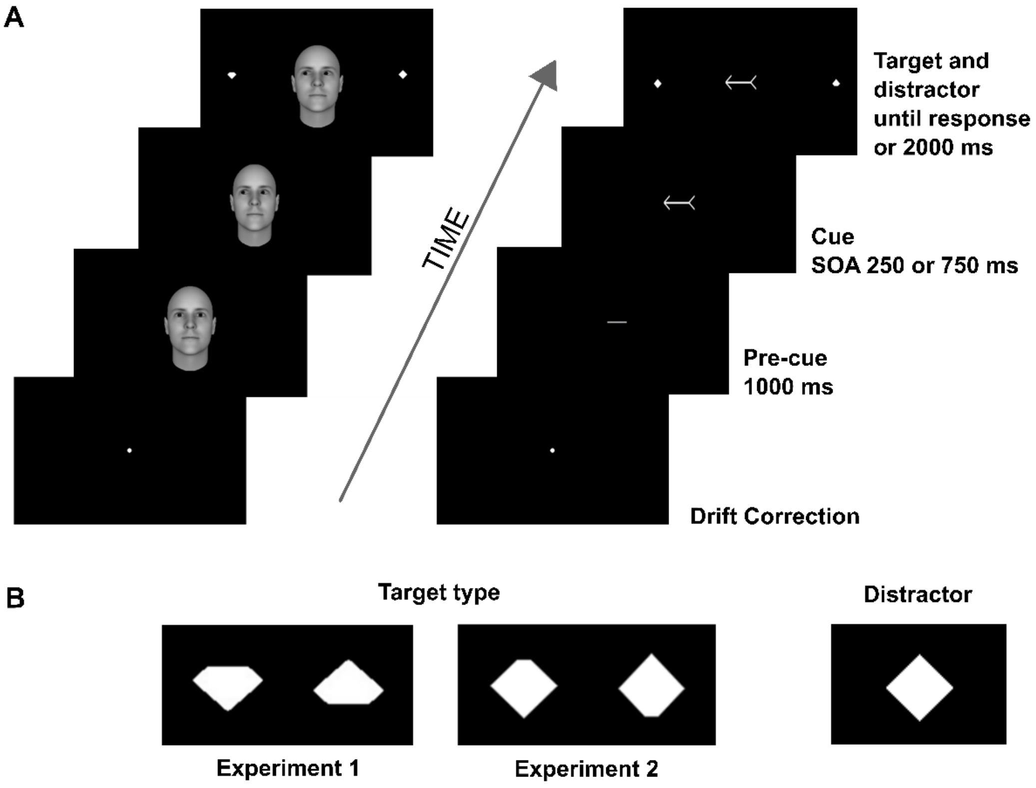

Figure 1. (A) Stimuli (not in scale) used in Experiment 1 and 2 as well as main trial sequence. **(B)** Target shapes used in the easy (Experiment 1) and difficult (Experiment 2) discrimination task. The distractor shape was always a whole diamond.

2.2.2 Results

I conducted confirmatory analysis on manual response times as well as exploratory analyses on specific measures of interest, i.e., saccadic frequency, amplitude and latency. Descriptive and inferential analyses were conducted using Matlab (The Mathworks; version R2016b), STATISTICA (Statsoft, Inc. 2004; version 7.0) and JASP (JASP Team, 2018; version 0.8.5.1, Windows 10). For all the dependent measures investigated the distribution of errors was evaluated to test for the assumption of normality using Shapiro-Wilk normality test as well as for the assumption of homogeneity of variances using Levene's test. Unless otherwise noted the data confirmed the assumptions.

Patterns of eye movements

Initial saccades were defined as eye movements with velocities and accelerations exceeding 30°/s and 8000°/s^2. Vertical eye movements, neither directed toward the target nor the distractor as well as eye movements with no landing coordinates were removed from the analysis (2.48% in gaze cue condition and 0% in the arrow cue condition). In the analyses I included saccades that were executed in trials where a correct manual response to the target was given. To get a general idea of whether eye movements were elicited, and if so, when they occurred relative to the presentation of the cue and following presentation of the target, I plotted a frequency distribution of initial eye movements for the duration of the trial, starting from the moment in which the cue was displayed (see Figure 2, panel A).

A first visual inspection of this figure reveals the shape of a bimodal distribution for each of the two SOA conditions. It seems that the early peaks of eye movements were triggered by the mere presence of the cue on the screen, from now on referred to as cue-elicited eye movements, while the later peaks of eye movements were executed in response to the presentation of the target and distractor, from now on referred to as target-elicited eye movements. In the short SOA, that is 250 ms, the first peak of eye movements was observed after the cue onset within the range of 150 and 350 ms (median value = 226 ms), while a second, higher peak appeared later on, with a median value of 471 ms. In the long SOA, namely 750 ms, the minor peak of eye movements after the cue onset had its median value at 265 ms and the higher peak at 961 ms.

For the cue-elicited saccade distributions I included all eye movements whose latency ranged from 150 up to 350 ms after the cue onset (see Figure 2, panel A) for both SOAs alike. Based on visual inspection of the distributions, I observed that the cue-elicited distribution started at 150 ms and there was a dip between the two distributions that occurred at 350 ms. For the target-elicited distributions, the interval appeared different for the short SOA compared to the long SOA. In the short SOA the cue and target-elicited distributions were very close together and overlapping. The dip that occurred at 350 ms corresponded with a lower criterion of 100 ms for the target-elicited saccades (see Figure 2, panel A). This lower latency boundary was considered to be the one that best separated the two distributions, although it is plausible that a partial overlap between late cue-elicited and fast target-elicited eye movements may be present. In the long SOA condition, the distribution of target-elicited saccades seemed to develop relatively earlier, and ranged from 80 ms after target onset until RT. Based on these clear bimodal frequency distributions, I split the data collected accordingly and I ran separate statistical analyses for cue and target-elicited eye movements.

Overall proportion of eye movements

The total proportions of eye movements were calculated dividing the actual number of saccades executed by each participant by the number of trials remained after filtering out incorrect, too fast and slow responses (see criteria described in the next section). Participants executed a saccade in response to the gaze cue on 19.5% (SD = 16.2%) of trials, whereas they moved the eyes in response to the arrow cue on 17.8% (SD = 13.8%) of trials. When I conducted a paired samples Wilcoxon test to check for significant effects of cue type, the analysis did not highlight any significant differences between social and non-social cues (W = 125, p = .47). On presentation of the target and distractor, the percentage of eye movements elicited increased. With respect to the target-elicited distributions, participants moved the eyes on average in 58.7% (SD = 42.7%) of trials in the gaze cue condition, while they did so in 53.6% (SD = 43%) of trials in the arrow cue condition. I repeated the same Wilcoxon analysis for target-elicited proportions and no difference between cues emerged (W = 114, p = .22). Note that the large amount of variation in percentage of eye movements highlights that the overall proportion of eye movements varied dramatically across participants. The results showed that there were some participants who made eye movements in nearly all trials, whereas some participants maintained fixation at the center of the display in the majority of trials.

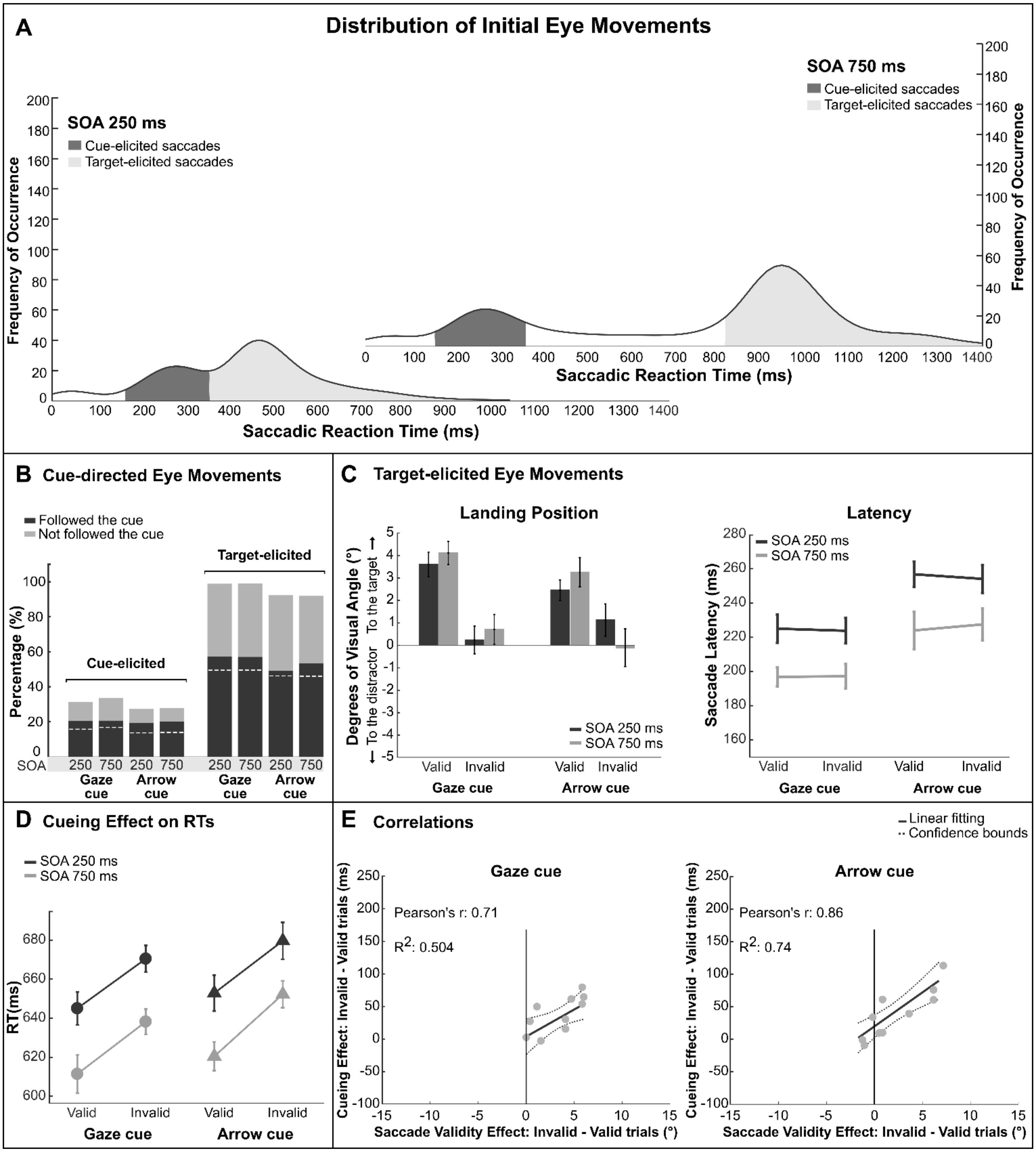

Figure 2. (A) Distributions of initial eye movements over time in Experiment 1, collapsed across cue condition. The 0 values on the x-axis represents the cue-onset, while on the y-axis raw frequencies of occurrence are represented. **(B)** Mean percentages of cue-directed eye movements in the *Eye-Movement (EM) Group* (N = 10)

on short and long SOAs in gaze- and arrow cue conditions. The white dashed line in each bar represents chance level at 50%. **(C) On the left:** Averaged target-elicited saccade landing positions on valid and invalid trials for gaze- and arrow cue conditions in the EM-group. On the y-axis, in degrees of visual angle, positive values represent saccades landed closer to the target and negative numbers indicate saccades landed closer to the distractor. **On the right:** Mean onset latencies for target-elicited saccades on valid and invalid trials for eye-gaze and arrow distractor conditions in the EM-group. **(D)** Mean response times of correct responses to the target on valid and invalid trials for gaze- and arrow cue conditions in Experiment 1. **(E)** Correlations between validity effect on target-elicited saccades against cueing effect on manual RTs for gaze- and arrow cue conditions in the EM-group. Descriptive Pearson's r values, coefficients of determination R^2 as well as a linear fitting with 95% confidence bound are represented.

All error bars denote within-subject standard errors, based on O'Brien & Cousineau (2014).

Behavioral cue-effect on RT

The overall accuracy rate was 97%. Incorrect responses, response time three standard deviations above the participant's average response time (RT) and timed-out trials were excluded from the analysis. The total percentage of trials discarded from the analysis was 4.25% for gaze cue condition and 3.78% for arrow cue condition. Mean response times were calculated and the distribution of error was evaluated to meet the assumptions for a repeated measures ANOVA. A 2x2x2 repeated measures ANOVA with Cue type (gaze vs. arrow), SOA (250 vs. 750 ms) and Validity (valid vs. invalid) was run. Main effects of **SOA** F (1, 19) = 29.54, $p < .0001$, $\eta^2_p = .61$ and **Validity** F (1, 19) = 29.68, $p < .0001$, $\eta^2_p = .61$ were found. Valid trials (M = 632 ms, SE = 19.8) were responded faster than invalid trials (M= 660, SE = 22.3) and trials in the longer SOA (M = 630 ms, SE = 20.3) were responded to faster than in the shorter SOA (M = 662, SE = 22) (see Figure 2, panel D). No other significant effect or interaction was found (all *Fs* < .81, *p*s > .37).

Because I was interested in the potential modulation of eye movements on manual RT, the behavioral RT data was also analyzed in dependency of whether or not participants made eye movements in response to the target presentation. Each participant was categorized based on the presence of eye movements after target onset; if on average 15 data points per cell were available in one of the categories (that is, eye movements vs no eye movements), that participant's data was added to the appropriate group. This led to a surprisingly even split with 10 participants in the so called *Eye Movement-Group* (EM-group, on average eye movements in 98.7% of trials for the gaze and 91.9% for the arrow cue condition) and 10 participants in the *no Eye Movement-Group* (no-EM-group, 18.6% of trials with eye movements for the gaze and 15.3% for the arrow cue). A mixed ANOVA with Group as between-subject factor and Cue type, SOA and Validity as within-subject factors was run on RTs. The group comparison revealed significant main effects of **SOA** (F (1, 18) = 33.12, p < .001, η^2_p = .65) and **Validity** across both groups (F (1, 18) = 30.95, p < .001, η^2_p = .63), though the validity effect was larger in the EM-group (M = 38.15 ms) compared to the no-EM-group (M = 15.4 ms), as indicated by a significant two-way interaction between **Group** and **Validity** (F (1, 18) = 5.59, p = .03, η^2_p = .24). In addition, participants in the EM-group responded slower than those who did not (main effect of **Group**, F (1, 18) = 7.13, p = .02, η^2_p = .28).

Cue-elicited eye movements

General direction.

This analysis concerns the proportion of initial eye movements made in response to the nonpredictive cues, prior to the target onset. Since the data from the no-EM group was too noisy, given that there were very few sample points per cell, analyses were conducted on the EM group only. For the EM-group, I calculated proportions of eye movements made in accordance to the direction indicated by the gaze and arrow cue. The results showed that in the short SOA, participants overtly followed the direction of the gaze cue in 66% of all trials and overtly followed the arrow cue in 68% of all trials. A similar result was found in the longer SOA, where observers followed the gaze cue in 62% and the arrow cue in 72% of the trials (see Figure 2, panel B for more details on the EM-group). I conducted a repeated measures

ANOVA on the proportions of cue-followed eye movements to check whether cue type affected the number of eye movements elicited in response to the cue, but no significant effect was found (all Fs < 0.8, ps > .4).

Saccade latency.

The dataset on latency included all initial saccades in the EM-group, whose latency was above the lower boundary, set at 150 ms. A 2x2 repeated measures ANOVA on the average saccadic reaction time was conducted, with Cue type (gaze vs. arrow) and SOA (250 vs. 750 ms) as within-subject independent variables (only one condition failed to satisfy the assumption of normality, with a p = .004). A main effect of **Cue type** F (1, 9) = 7.67, p = .02, η^2_p = .46 was found. Gaze cue condition triggered faster eye movements (M = 256 ms, SE = 5.05) than the arrow cue (M = 270 ms, SE = 4.4). No other main effects or interaction reached significance (all *Fs* < .60, *p*s > .45).

Target-elicited eye movements

Saccade landing position.

Saccade landing position was obtained measuring the distance in degrees of visual angle between the x and y coordinates of the target center and the ending coordinates of each saccade, such that 0° of visual angle represented an eye movement landed on the target and 22° represented an eye movement landed on the distractor (note that in Figure 2, panel C, the measure is re-referenced to a scale of signed values for clarity purpose; positive values represent saccades that landed closer to the target, negative values represent values closer to the distractor). Outliers were removed by means of a three standard deviations of the mean criterion. A 2x2x2 repeated measures ANOVA on the average distance from the target in degrees of visual angle was run. Cue type (gaze vs. arrow), SOA (250 vs. 750 ms) and validity (valid vs. invalid) were the within-subjects independent variables. A main effect of **Validity** F (1, 9) = 15.2, p = .004, η^2_p = .63 was found. Valid trials (M = 7.75°, SE = .53), resulted in larger saccades towards the validly cued target position compared to invalid trials (M = 10.6°, SE = .88). No other main effect or interaction reached significance (all *Fs* < 3.28, *p*s > .1).

Saccade latency.

Saccade latency was defined as the time between the target onset and the initiation of a saccade. Saccade latencies smaller than and 100 ms for the short SOA and 80 ms for the long SOA, together with latencies slower than three standard deviations from the mean of each participant were not taken into consideration for further analysis. A 2x2x2 repeated measures ANOVA on the average saccadic reaction times was run, with Cue type (gaze vs. arrow), SOA (250 vs. 750 ms) and validity (valid vs. invalid) as within-subject independent variables. A main effect of **Cue type** *F* (1, 9) = 5.86, *p* = .04, η^2_p = .39 and **SOA** *F* (1, 9) = 22.12, *p* = .001, η^2_p = .71 was found (see Figure 2, panel C). On average, gaze cue triggered faster eye movements (M = 211 ms, SE = 11.2) compared to the arrow cue (M = 241 ms, SE = 19.6). In trials where the SOA was shorter, average saccade reaction time was longer (M = 240 ms, SE = 14.8) than in trials with longer SOA (M = 211 ms, SE = 15.2). No other main effects or interaction reached significance (all *Fs* < 1.38, *p*s > .27).

Correlations

To directly explore the relationship between overt performance and behavioral effect on manual RTs, I plotted the relationship between the validity effect on manual RTs against the validity effect on landing positions of target-elicited saccades for the EM-group. To this end, I considered only trials where both RT and eye movement data were available. The validity effect on RT was calculated by subtracting the average RT on valid trials from the one in invalid trials. Following the same procedure, I computed the validity effect on target-elicited distance to target subtracting the values in valid trials from the corresponding ones in invalid trials. Strong positive linear correlations for both gaze (Pearson's *r*(10): .71; 95% confidence interval [CI] = .14, .92; R^2 = .50) and arrow cue condition (Pearson's *r*(10): .86; 95%

confidence interval [CI] = .50, .97; $R^2 = .75$) were found (see Figure 2, panel E). In other words, for both cues the relationship indicates that the greater the difference in saccadic landing position in response to invalid and valid cues, the greater the difference in RT between invalid and valid cues.

2.2.3 Discussion

In Experiment 1, I investigated whether overt orienting can help explain behavioral manual responses towards social and non-social cues. Participants performed a discrimination task and were presented with nonpredictive central gaze and arrow cues at two different cue-target SOAs. There were three main findings. First, my data replicated previous and well-documented cueing effects on response times (Driver et al., 1999; Friesen & Kingstone, 1998; Galfano et al., 2012; Heimler, van Zoest, Baruffaldi, Rinaldi, et al., 2015b; Langton & Bruce, 1999; Ristic et al., 2002). Although participants were aware of the fact that both cues were nonpredictive, they responded faster to valid cues compared to invalid cues. In addition, when the interval between the cue and the target was longer, behavioral responses were faster. This latter result is a well-known phenomenon called cue-target foreperiod effect and reflects a general preparatory process (Bertelson, 1967). I found no significant difference in the magnitude of the cueing-effect of the gaze versus the arrow cue, suggesting that the two cues were similar in the ability to trigger automatic orienting (Stevens, West, Al-Aidroos, Weger, & Pratt, 2008).

Second, the proportion of eye movements made in Experiment 1 highlighted that for some observers oculomotor responses were not necessary to perform the task accurately. Nevertheless, even if participants were asked to maintain fixation throughout the experiment, my results show that saccadic eye movements were often made during the task. In particular, a group of individuals triggered eye movement responses before their manual response. While in the majority of cases cue-elicited eye movements were found to follow the direction indicated by the uninformative cues, target-elicited saccades generally landed closer to valid targets only. Invalid trials did not elicit a reliable overt response, neither to the distractor nor to the target. Although cue type did not appear to affect behavioral responses nor landing positions, an effect of cue-type emerged with respect to saccade latency, both for cue-elicited and target-elicited movements. The results showed that saccades initiated in response to gaze-cues were generally faster than saccades elicited in response to arrow-cues. In this sense, the saccade latency data supported the hypothesis that overt orienting in response to a gaze cue is more reflexive compared to responses to an arrow cue. Additionally, target-elicited saccade latencies were also modulated by SOA, as saccadic reaction times (SRTs) were slower in the short SOA. The pattern was consistent with the foreperiod effect found in the behavioral data. However, critically, saccade latency was not modulated by validity and saccades were equally fast regardless of whether the cue was valid or invalid.

Third, linear correlations between the validity effect on target-elicited saccades and the manual validity effect on RT disclosed a strong association between overt and covert performance for both cue conditions. The amplitude of saccades made in response to invalid and valid trials was strongly associated to the magnitude of the validity effect on RTs. However, I am aware of the fact that the main limitation of this finding in Experiment 1 is that it is based on only half of the experimental sample, as only half the sample provided sufficient eye movement data.

To sum up, Experiment 1 allowed making a first inspection of the relative contribution of overt selection during a simple discrimination task. Oculomotor responses were associated with overall slower manual RTs and, when present, they landed closer to the valid target location. In addition, manual responses and eye movement landing position patterns did not differ in dependency of the cue, suggesting that the overt mechanism of selection operates similarly irrespective of the nature of the central cue presented. Though saccade latencies were affected by the type of cue presented, this difference between social and non-social cues was not carried over to the manual RTs. This may be the case because eye movements were not instrumental in correctly identifying the target. In fact, the strong relationship between eye movements and the cueing effect on RT was found in 10 out of 20 participants, suggesting that individual differences played an important role in the final oculomotor behavior. While the sample size of 20 participants proved sufficient in terms of power for manual measures, in terms of saccadic dependent measures it was ambivalent, i.e., it was appropriate for saccade amplitude, but not fully convincing for saccade latency. Hence, this further motivated Experiment 2 where I increased the need for eye movements yielding more data for these dependent measures.

2.3 Experiment 2

To further investigate the association between oculomotor responses and orienting of spatial attention to social and non-social cues, I designed a second experiment. The aim of the second experiment was to make eye movements instrumental in the task, while keeping experimental instructions identical. I manipulated the difficulty of the discrimination task by reducing the size of missing part of the target diamond. Because identification of the missing part of the target would benefit from closer foveal scrutiny, I hypothesized that this difficulty manipulation would lead to an overall increase in the rate of eye movements. I also speculated that saccades could be biased more strongly by the central cues. I further hypothesized that the increased difficulty of the task would slow down overall RT and possibly decrease accuracy, but that the overall manual cueing effect should be similar compared to Experiment 1. Again, if saccade landing position and manual RT are associated, I should be able to replicate the strong correlation found in Experiment 1.

2.3.1 Methods

Participants

Twenty new young adults aged 20-36 (M = 25.6 years old; SD = 4.4; females = 10; all right-handed) were recruited from the local student population of the University of Trento and were tested in the CIMeC psychophysics laboratories. All participants had normal or corrected-to normal vision. This research was conducted according to the principles expressed in the Declaration of Helsinki and informed consent was obtained from each participant. All participants received either a reimbursement of 7 €/hour for their participation or University credits. To ensure that my experiment had enough statistical power to test the presence of a relationship between saccadic and manual validity effects found in Experiment 1, effect sizes of validity on manual RT ($\eta^2_p = .61$) and on saccadic amplitude ($\eta^2_p = .63$) from Experiment 1 were used to estimate the new effect size. With a minimum sample size of eleven participants a desired statistical power of .90 for these effects on validity could be reached, correcting for publication bias (Anderson et al., 2017). As in Experiment 1, my sample of twenty observers was appropriate for testing these effects.

Stimuli, Procedure and Design

The monitor was replaced between experiments. Stimuli in the second experiment were presented on a 23.6-inch ViewPixx EEG monitor (100 Hz; resolution 1920x1080) that was set up with a viewing distance of 60 cm. Stimulus presentation was controlled by a NVIDIA Quadro K620 graphics card. The remainder of the design, materials and procedure of Experiment 2 were identical to Experiment 1, except for the target stimulus, whose color was slightly changed to maintain the same luminance as in the previous Experiment with the previous screen (RGB: 190, 196, 208). The missing part of the target was a triangle, whose height was one tenth of the target total height (see Figure 1, panel B).

I modified the target shape to be sure that people could not discriminate it without moving the eyes. However, since I did not want to bias observers into a different strategy, for example of making more eye movements from the start compared to Experiment 1 or of avoiding eye movements before the actual target onset, I provided participants with the same instructions as in Experiment 1. Therefore, participants were asked to maintain fixation and to be as accurate as possible on the discrimination task. Again, similar to Experiment 1, no feedback was provided on eye movement behavior and fixation was by no means reinforced.

2.3.2 Results

For all the dependent measures I investigated, the distribution of error was evaluated to test for the assumption of normality using Shapiro-Wilk normality test as well as for the assumption of homogeneity of variances using Levene's test. Unless otherwise noted the data confirmed the assumptions.

Patterns of eye movements

Visual inspection of the total frequency of eye movements over time reconfirmed the existence of two bimodal distributions. In the short SOA, I observed a peak of eye movements that followed the cue onset (median value = 219 ms) and a second, higher peak after the target appeared on the screen (median value = 412 ms). In the long SOA, the two peaks respectively emerged after the cue onset (median value = 268 ms) and later on, in response to the target and distractor onset (median value = 906 ms). Consequently, I could again discriminate cue-elicited eye movements from target-elicited eye movements (see Figure 3, panel A). Initial saccades were defined using the same criteria explained in the Results Section of Experiment 1 and I selected cue-elicited saccades and target-elicited saccades within the same intervals reported in Experiment 1. I ran the same analysis on proportion of eye movements, landing position and latency, discarding further 0.19% of trials in the gaze cue condition and 1.3% in the arrow cue condition.

Overall proportion of eye movements

The total proportions of eye movements were calculated adopting the criteria reported in Experiment 1. Cue-elicited eye movements were triggered on 33.8% (SD = 15.6%) of trials in the gaze cue condition and on 41.5% (SD = 19%) in the arrow cue condition (Figure 3, panel B), and the proportions did not vary as a function of cue type (paired samples Wilcoxon test, W = 54, p = .06). In addition, saccades in response to the target and distractor in the gaze cue condition occurred on average in 99% (SD = 1.2%) of trials and in 99.5% (SD = 0.8%) of trials in the arrow cue condition; there were no significant differences between cues (paired samples Wilcoxon test, W = 27.5, p = .22). Note that the task manipulation almost doubled the overall percentage of eye movements and considerably reduced the variability compared to Experiment 1, showing that the manipulation worked as intended.

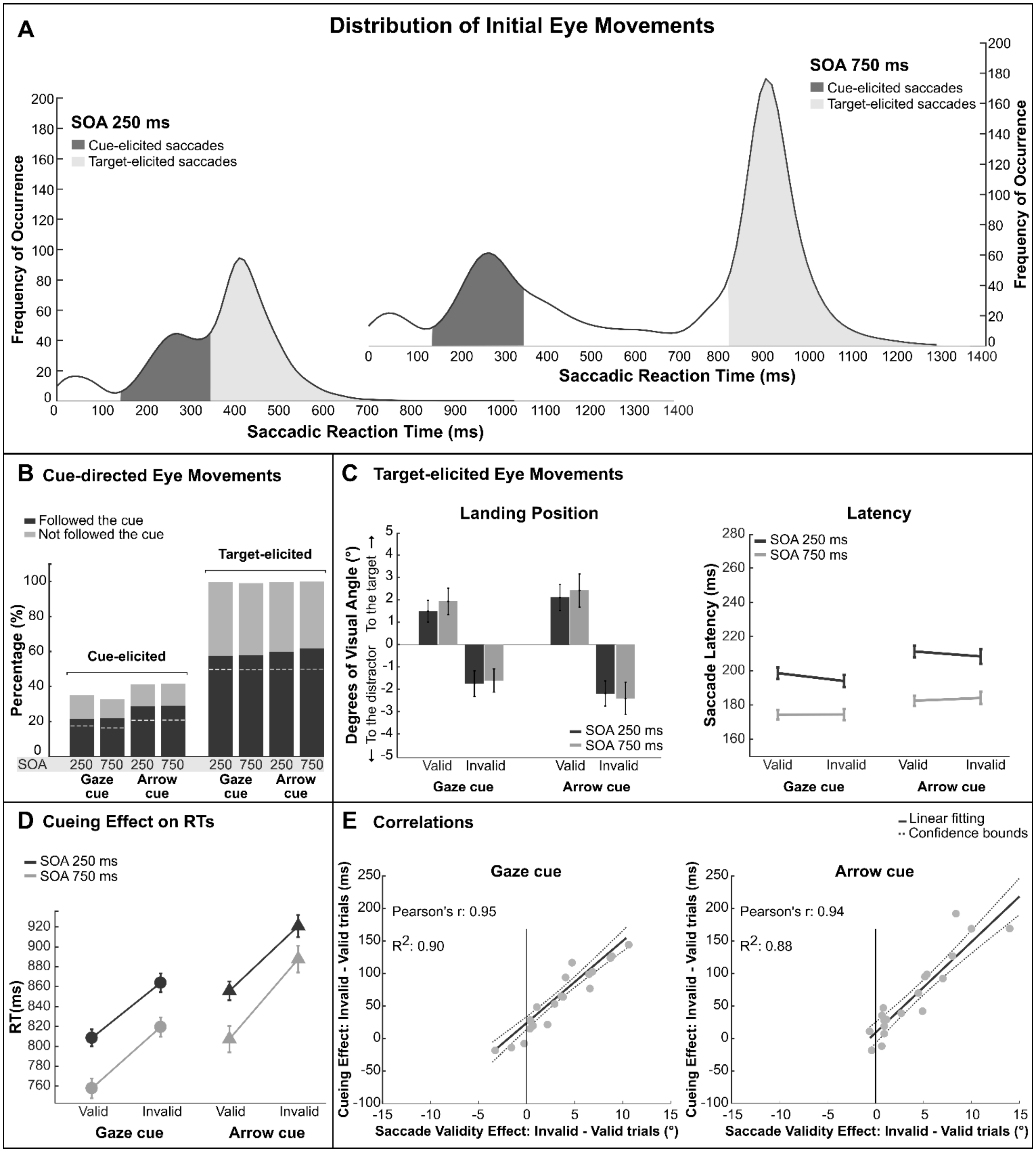

Figure 3. (A) Distributions of initial eye movements over time in Experiment 2, collapsed across cue condition. **(B)** Mean percentages of cue-directed eye movements on short and long SOAs in gaze- and arrow cue conditions. The white dashed line in each bar represents chance level at 50%. Note that this time all participants were included

in the dataset. **(C) On the left:** Averaged target-elicited saccade landing positions on valid and invalid trials for gaze- and arrow cue conditions in Experiment 2. On the y-axis, in degrees of visual angle, positive values represent saccades landed closer to the target and negative numbers indicate saccades landed closer to the distractor. **On the right:** Mean onset latencies for target-elicited saccades on valid and invalid trials for eye-gaze and arrow distractor conditions in Experiment 2. **(D)** Mean response times of correct responses to the target on valid and invalid trials for gaze- and arrow cue conditions in Experiment 2. **(E)** Correlations between validity effect on target-elicited saccades against cueing effect on manual RTs for gaze- and arrow cue conditions in Experiment 2. Descriptive Pearson's r values, coefficients of determination R^2 as well as a linear fitting and 95% confidence bounds are also depicted.

All error bars represent within-subject standard errors, based on O'Brien & Cousineau, 2014.

Behavioral cue-effect on RT

The overall accuracy rate was again 97% and therefore no further analysis on accuracy was carried out. Mean response times were calculated and outliers were removed using a 3 standard deviation criterion. The proportion of trials discarded from the analysis was 2.90% for the gaze cue condition and 2.96% for the arrow cue condition. A 2x2x2 repeated measures ANOVA with Cue type (gaze vs. arrow), SOA (250 vs. 750 ms) and Validity (valid vs. invalid) was run.

Main effects of **Cue type** F (1, 19) = 29.91, $p < .0001$, $\eta^2_p = .61$, **SOA** F (1, 19) = 33.32, $p < .0001$, $\eta^2_p = .64$ and **Validity** F (1, 19) = 29.61, $p < .0001$, $\eta^2_p = .61$ were found. Gaze cues (M = 812 ms, SE = 15.8) were responded to faster than arrow cues (M = 868 ms, SE = 16.5), longer SOA (M = 818 ms, SE = 16.4) were faster than shorter SOA (M = 862 ms, SE= 16.4) and valid trials (M = 807 ms, SE = 16.3) resulted in faster response times than invalid trials (M = 872 ms, SE = 16.7) (see Figure 3, panel D). No other significant interactions were found (all *F*s < 1.21, *p*s > .28).

In addition, I directly compared behavioral performance of Experiment 1 and Experiment 2 to see whether the task modulated the validity effect on RTs, since Experiment 2 required participants to move the eyes to identify the target shape. A mixed ANOVA with Experiment as between-subject factor and Cue type, SOA and Validity as within-subject factors was performed on reaction times. Main effects of **Experiment** *F* (1, 38) = 55.48, *p* < .001, η^2_p = .59, **Cue type** *F* (1, 38) = 18.96, *p* < .001, η^2_p = .33, **SOA** *F* (1, 38) = 62.13, *p* < .001, η^2_p = .62 and **Validity** *F* (1, 38) = 50.83, *p* < .001, η^2_p = .57 were found. The increased difficulty of the task had a significant impact on RTs, which were overall slower (M = 840 ms, SD = 18.4). Furthermore, a significant two-way interaction between **Experiment** and **Cue type** (*F* (1, 38) = 9.13, *p* = .004, η^2_p = .19) revealed that the gaze cue was more beneficial to RTs compared to the arrow cue when the task was more difficult. In addition, the validity effect on RTs was larger in Experiment 2, as pointed out by the significant two-way interaction between **Experiment** and **Validity** (*F* (1, 38) = 8.41, *p* = .006, η^2_p = .18).

This result suggests that task-difficulty had a distinct effect on the overall RT of the arrow cue but not the gaze cue in Experiment 2 compared to Experiment 1. However, rather than being driven by task-difficulty, this may be a result of the presence of eye movements, which were more abundant in Experiment 2 than in Experiment 1. The manual results in Experiment 1 contained all participants, including those who made very little eye movements. To test the idea that the eye movements distinctively speed manual RTs to gaze cues but not arrow cues, I compared the manual responses of the Eye Movement-Group of Experiment 1 and compared to all of the participants in Experiment 2. A between experiment ANOVA on the aforementioned samples, including Cue type (gaze vs. arrow) as within-subjects factor and Experiment (1 vs. 2) as between-subjects factor was run. The analysis revealed a main effect of **Cue type**, F(1, 28) = 25.4, p < .001, η^2_p = .47, a main effect of **Experiment** F(1, 28) = 25.41, p < .001, η^2_p = .47, but no interaction between cue type and experiment F(1, 28) = 2.5, p = .122, suggesting that when I matched for eye movements, both experiments highlighted a comparable gaze cue advantage on overall RTs. When the EM-Group was considered in isolation, no significant cue-dependent difference in overall RT was found (repeated measures ANOVA, F(1, 9) = 4.94, p = .053).

Cue-elicited eye movements

General direction.

I calculated the proportion of eye movements directed towards the location indicated by the gaze and arrow cue, for both SOAs (see Figure 3, panel B). In the short SOA, participants followed the cue respectively on 62% (gaze cue condition) and 69% (arrow cue condition) of trials. Similarly, in the longer SOA the proportion in percentage were 72% (gaze cue) and 68% (arrow cue). The repeated measures ANOVA on the proportions of cue-followed eye movements did not highlight any significant effects of cue type or SOA (all Fs < 2.03, ps > .17) on the general direction of cue-elicited saccades.

Saccade latency.

As I did in Experiment 1, in the analysis I considered all saccadic reaction times longer than 150 ms. A 2x2 repeated measures ANOVA on the saccadic reaction time was performed, with Cue type (gaze vs. arrow) and SOA (250 vs. 750 ms) as within-subject independent variables. A main effect of **Cue type** $F(1, 19) = 11.84$, $p = .003$, $\eta^2_p = .38$ was found. The gaze cue condition triggered faster eye movements (M = 262 ms, SE = 3.32) than the arrow cue (M = 275 ms, SE = 3.51). No other main effects or interactions reached significance (all *F*s < .29, *p*s > .59).

Target-elicited eye movements

General direction.

I calculated the proportion of eye movements directed towards the location indicated by the gaze and arrow cue, for both SOAs (see Figure 3, panel B). In the short SOA, participants followed the cue respectively on 62% (gaze cue condition) and 69% (arrow cue condition) of trials. Similarly, in the longer SOA the proportion in percentage were 72% (gaze cue) and 68% (arrow cue).

Saccade landing position.

I followed the same procedure of Experiment 1 to calculate saccade landing position. A 2x2x2 repeated measures ANOVA was conducted on the average distance from the target in degrees of visual angle; Cue type (gaze vs. arrow), SOA (250 vs. 750 ms) and Validity (valid vs. invalid) constituted the within-subject independent variables (see Figure 3, panel C). A main effect of **Validity** *F* (1, 19) = 22.97, *p* < .001, η^2_p = .55 was found. Saccades in valid trials (M = 9.39°, SE = .45) landed closer to the target, whereas saccades in invalid trials landed closer to the distractor (M = 13.36°, SE = .46). No other main effect or interaction reached significance (all *Fs* < 1.45, *p*s > .24).

In addition, I compared Experiment 1 and Experiment 2 with respect to the landing position of eye movements to see whether the difficulty of the task had an impact on saccades amplitude. A mixed ANOVA with Experiment (1 vs. 2) as between factor and Cue type (gaze vs. arrow) and Validity (valid vs. invalid) as within-subject factors was performed. A main effect of **Validity** *F* (1, 28) = 28.09, *p* < .001, η^2_p = .50 was present. Saccades landed closer to the target in valid trials (M = 8.57°, SE = .37), compared to invalid trials (M = 11.98°, SE = .45). Furthermore, a main effect of **Experiment** *F* (1, 28) = 18.84, *p* < .001, η^2_p = .40) was found. In Experiment 1 I confirmed that landing positions of initial eye movements were biased to the valid target position only (M = 9.17°, SE = .41), while in Experiment 2 initial eye movements followed the position indicated by the nonpredictive cue (M = 11.38°, SE = .29). No other main effect or interaction reached significance (all *Fs* < 2.05, *p*s > .16).

Saccade latency.

In order to satisfy the assumption of normality, I performed a logarithmic transformation of the latency dataset (Shapiro-Wilk normality test, all ps > .161). A 2x2x2 repeated measures ANOVA was run with Cue type (gaze vs. arrow), SOA (250 vs. 750 ms) and Validity (valid vs. invalid) as within-subject factors. This analysis revealed a main effect of **Cue type** *F* (1, 19) = 6.64, *p* = .018, η^2_p = .26, and **SOA** *F* (1, 19) = 68.72, *p* < .0001, η^2_p = .78 (see Figure 3, panel C). Faster saccades were triggered by the gaze cue (M = 183 ms, SE = 1.032) compared to the arrow cue (M = 193 ms, SE = 1.036). In trials where the SOA was shorter, average saccade reaction time was slower (M = 201 ms, SE = 1.03) than in trials with longer SOA (M = 176 ms, SE = 1.034). No other main effects or interactions were significant (all *Fs* < 2.8, *ps* > .11).

Correlations

To investigate the direct relationship between eye movements and cueing effect on RT, I plotted the relationship between the validity effect on manual RTs against the validity effect on landing positions of target-elicited saccades. I followed the criteria of Experiment 1, but this time all participants provided sufficient data and were all included in the analysis. Again, I calculated the validity effect on RTs and target-elicited distance to the target subtracting the values in valid trials from the corresponding ones in invalid trials. Strong positive linear correlations for both gaze (Pearson's *r* (20): .95; 95% confidence interval [CI] = .87, .98; R^2 = .90) and arrow cue condition (Pearson's *r* (20): .94; 95% confidence interval [CI] = .85, .98; R^2 = .88) were found, confirming the findings of Experiment 1 but this time in a larger dataset (see Figure 3, panel E).

2.3.3 Discussion

In Experiment 2 the discrimination task was made more difficult in order to make eye movements instrumental in the task. The results showed that in comparison to Experiment 1 the proportions of eye movement increased substantially. Taken together, these findings indicate that the task manipulation effectively raised the need for overt shifts. In addition, relative to Experiment 1 overall RTs slowed down, indicating that participants needed more time to resolve the identity of the target. Interestingly, the behavioral performance highlighted a significant difference between cue conditions, where observers were faster to respond when the nonpredictive cue was the eye gaze. However, this new cue-dependent difference was unlikely due to task-difficulty and Experiment 2 being more difficult. When I checked the results against those of Experiment 1 looking at only the observers who made eye movements (N = 10), I found a very similar difference in the Experiment 1, in that gaze was responded to faster than the arrow. Thus, regardless of difficulty, in the presence of eye movements, manual responses to gaze-stimuli were faster than to arrow-stimuli, which is line with the general results on saccade latency.

Looking at the pattern of eye movements, the analysis of the cue-elicited eye movements confirmed that participants tended to follow the cue. Saccade landing positions in the target-elicited distribution were affected by cue validity. Neither the cue-elicited nor the target-elicited saccades were affected by the type of cue, whether it was a gaze- or arrow cue. Unlike the results in Experiment 1, invalid cues elicited an overt response away from the target in the general direction of the distractor in Experiment 2. While the analysis of initial saccade landing positions did not reveal reliable differences between social and non-social cues, the analyses on saccade latency did. Prior to target onset, cue-elicited saccades were faster when triggered by the social cue. Similarly, target-elicited saccadic reaction time varied in dependency of the cue presented, with faster saccadic RTs when the cue was the gaze. Hence, evidence from Experiment 2 is in favor of the notion that social cues may elicit more reflexive shifts in overt attention than do non-social cues. In addition, this differentiation seemed to extend up to the final response, in the sense that gaze cue-associated overall RTs were speeded up. However, critically, this difference in saccade latency between cues did not carry over to differences in validity effects on RT nor differences in landing positions across cues. Finally, correlations between the cueing effect on RT and validity effect on eye movements confirmed the trend shown in Experiment 1, adding converging evidence for a strong association between the initial landing position of the oculomotor response and the final manual response.

2.4 General Discussion

In the present work I investigated the impact of spontaneous oculomotor behavior on attentional performance. My approach extends previous research, in the sense that it enabled the examination oculomotor performance and attentional orienting at different moments in time and it demonstrates that spontaneous eye movements are present even before the occurrence of a specific event, i.e. the target appearance, and even when the task does not require overt responses.

First, my data reveal the cue had an immediate impact on overt performance that was already present in the cue-elicited saccadic responses. In previous work on covert attention participants' gaze was not tracked, so the impact of the uninformative cues on cue-elicited eye movements could not be measured with RT or inferred from RT patterns. Previous studies on overt attention that revealed potential differences between these cues have focused on target-elicited saccade latencies, not considering the dynamic deployment of attention over time and its consequences on different oculomotor parameters.

Second, I found that cue-type has a distinct impact on oculomotor components. While saccade latencies were affected by the type of cue, both before and after the target onset, saccade landing positions were not.

Starting from the '90s, findings have pointed out that centrally presented nonpredictive cues can trigger reflexive orienting of attention (e.g. Driver et al., 1999; Friesen & Kingstone, 1998; Galfano et al., 2012; Heimler et al., 2015b; Hommel et al., 2001; Langton & Bruce, 1999; Ristic et al., 2002; Ristic & Kingstone, 2005; Tipples, 2002; however, see Gibson & Bryant, 2005; Vecera & Rizzo, 2004, 2006). In my study, the observed cueing effects on RTs are in line with a wide range of studies that demonstrate how both uninformative gaze as well as arrow cues result in orienting of covert attention, showing that valid trials are responded to faster than invalid trials. Despite the stark perceptual differences between the gaze and arrow cue in terms of complexity, results of Experiment 1 and 2 show that the influence of both nonpredictive cues on spatial attention, in terms of validity effects, was comparable. However, manual RTs represent the final result of orienting of attention and selection. Dynamic visual processing is difficult to access using RTs only. In the present work I recorded eye movements during the cueing task to examine their temporal evolution and investigated how they contribute or influence the final manual response. Previous work on overt attention did not collect manual RTs and was based on specific instructions, which anchored saccades execution at a certain point in time (Kuhn & Benson, 2007; Kuhn et al., 2009; Kuhn & Kingstone, 2009). Differently from previous research on overt attention, the present work focused on the impact that spontaneous oculomotor behavior may have on attentional performance. Consequently, I did not specifically and explicitly instructed participants to start an eye movement at a certain point in time or to a specific target. Rather than giving such instructions, I asked participants to try and maintain fixation during the task, similar to previous studies on covert orienting of attention. In Experiment 1, I observed variability in oculomotor behavior and this may reflect the presence of individual differences in the awareness of observers' own oculomotor responses. Recent work has shown how eye movements are very often not under volitional control and even though observers may feel that they are following instructions and fixating on the center of the screen, saccadic responses might show otherwise (Clarke, Mahon, Irvine, & Hunt, 2017; Mahon, Clarke, & Hunt, 2018). My second experiment intended to overcome the limitation of the first experimental design regarding the large variability between individual participants as well as to test the statistic reliability of analyses done in Experiment 1. I further explored the role of eye movements by checking whether the patterns of results remained consistent across two tasks differing in difficulty. A simple manipulation of the target shape proved to be very effective in increasing the need for eye movements, while preserving the main features of the cueing task.

In my experiments, I distinguished two main distributions of eye movements. The first one likely represents overt responses to the presentation of the central cues, before the target and distractor are displayed. The second distribution reflects eye movements made once the target and distractor have appeared on the screen. What do these event-related eye movements reveal about the processing of nonpredictive central cues? On the one hand, the examination of cue-elicited saccades confirmed that overt performance is sensitive to uninformative central cues, irrespective of whether the cue was social or not. Furthermore, saccade landing positions of target-elicited saccades were also comparable in the two cue conditions. When the task was easy in Experiment 1, saccadic eye movements landed closer to the target only in the valid condition. It seems that these eye movements were mainly executed to get a better look at the target to support target discrimination. This pattern changed when the task became more difficult, in the sense that saccades appeared to follow the nonpredictive central cues, irrespective of their validity. Critically, all of these measures of oculomotor behavior failed to reveal any differences between social and non-social cues. My work shows that this basic form of social attention, i.e. attentional orienting in response to eyes, is similar to non-social orienting of attention in most oculomotor measures.

The only difference I found between social and non-social cues was in saccade latency, which depended distinctively on the type of cue. In this regard, significant differences in saccade latency may support the notion that eye gaze cues are processed more rapidly than non-social cues and that gaze cues lead to more reflexive orienting of overt attention. It may be the case that this difference can be explained by low-level differences between the gaze-cue and the arrow-cue. The gaze-cue was far more complex compared to the line drawing of the arrow. Yet, despite the fact that the stimuli were so vastly different, my results showed that they influenced manual behavior in a very similar way. Previous studies that more systematically controlled for low-level differences of social and non-social stimuli, as well as included instructions about the type of eye movement to execute, also reported faster latencies in response to the gaze cue for both for correct saccades (Kuhn et al., 2009) and erroneous saccades (Kuhn & Benson, 2007). In an attempt to increase ecological validity of the social stimuli, I used a more realistic eye gaze cue; regardless of stimulus-complexity differences, my data are in line with previous findings on saccade latency showing faster response to gaze than arrows. Importantly, both cue-elicited and target-elicited eye movements uncovered this subtle difference between social and non-social cues and this further shows that saccade latencies are immediately affected by the type of cue, independent of the presentation of the target or task.

Interestingly, this effect appears to be preserved also in overall RTs, providing evidence for a cue-dependent association between oculomotor and manual responses. While Experiment 1 highlighted a trend in this direction in the subgroup of individuals that relied more on eye movements, Experiment 2 confirmed this result in a bigger sample of participants. Irrespective of task difficulty, the gaze cue advantage on latency and overall RT was present when I matched samples for eye movements. The fact that eye-gaze has a greater impact on selection may find its roots in difference in biological relevance; while the eye gaze is important for humans to develop social interaction and joint attention (Corkum & Moore, 1995), the arrow cue is typically regarded as non-biologically relevant. Several experimental studies have tested this hypothesis comparing the social and non-social cues both in terms of their behavioral effects as well as the possible neural mechanisms underlying this form of reflexive orienting (Carlin & Calder, 2013; Dalmaso, Galfano, Tarqui, Forti, & Castelli, 2013; Friesen et al., 2005, 2004; Galfano et al., 2012, 2011; Hietanen et al., 2008, 2006; Kingstone, Tipper, Ristic, & Ngan, 2004; Langdon & Smith, 2005; Ristic et al., 2002, 2007). However, the debate is far from being settled. While several experimental and neuropsychological studies have provided evidence in favor of the idea that gaze cue processing is more reflexive and less affected by voluntary control of attention, and that additionally these cues rely on diverse neural networks (Akiyama et al., 2006; Friesen et al., 2005, 2004; Hietanen et al., 2008; Kingstone et al., 2000; Ristic et al., 2002; Ristic & Kingstone, 2005; Ristic et al., 2007), others have found no evidence to suggest differences between the social and non-social cues (e.g. Galfano et al., 2012; Kuhn & Benson, 2007; Kuhn & Kingstone, 2009; Tipples, 2008).

While the present patterns of results on saccade latency and on manual overall response times support this distinction, they also suggest that this difference between gaze and arrow cues is apparent only in the presence of eye movements. No cue modulation on RT was found in the subgroup of participants that did not move the eyes in Experiment 1, but it was clearly present in Experiment 2, where all participants needed eye movements for the discrimination task. It may be possible that eye contact prompts observers to make eye movements more rapidly and to respond faster, thus highlighting the gaze cue advantage on latency and overall RT. This effect may stem from a general alerting effect caused by the eyes (see also Kuhn & Benson, 2007; Kuhn & Kingstone, 2009), or it may represent a unique social feature of attentional orienting to social cues (Marotta, Román-Caballero, & Lupiáñez, 2018). Future research could be aimed at specifying in more detail in which contexts such facilitation emerges and which are the possible factors driving this effect. Simplifying the qualitative features of the face or, more challenging, enriching the sensory characteristics of the non-social cue could facilitate the comparison between social and non-social cues in different situations. In my case, it could be argued that very different low-level features like saliency and size may have played a role in creating the advantage on overall RTs observed in the gaze cue condition. Nonetheless, even if saccades were elicited faster in response to gaze cues, not only when the target was presented but also before that moment, it is important to note that the magnitude of the validity effect on RT was not affected by cue type.

While saccade latency did not vary as a function of validity, evidence for a strong link between attention and eye movements was found in the association between the validity effect on saccade landing positions and the cueing effect on RTs. Moreover, this distinction between saccade latency and landing position further suggests that not all aspects of overt selection are affected by the type of cue. Regardless of cue type, landing position of target-elicited initial eye movements in valid and invalid trials was tightly associated with the magnitude of the final validity effect on RTs. Taking into account that initial target-elicited saccades had their peak at around 200 ms after the target onset and responses occurred 400-500 ms later, my data endorses the statement that nonpredictive cues elicit a form of orienting that is resistant to volition and persists over time. I confirmed this robust association also in a larger sample size and with bigger datasets at disposal (Experiment 2). Yet, more research is required to verify the existence of a causal relationship between direction of initial eye movements and cueing effects on manual responses. As I did not directly manipulate oculomotor measures, any interpretation of the causal relationship between landing position and manual cueing effect remains premature and more research is needed to test it. Nonetheless, the examination of eye movements in a spatial cueing paradigm revealed the presence of distinctive associations between diverse oculomotor components and manual RT. My data demonstrate that saccade latency is cue-dependent and that the gaze cue facilitation seems to extend to the manual responses. Conversely, landing position is validity-dependent and is tightly associated with the magnitude of cueing effects on RT.

These findings have implications for our understanding of the relationship between attention and eye movements. My study suggests that different components of eye movements seem to be differently associated with the observed final manual response; this shows that the relationship between attentional orienting and eye movements is not straightforward. Although interpretations of this distinction of oculomotor parameters are somewhat premature and further research is needed, they seem to suggest that the when and the where of eye movements have different properties and separate links to manual responses, at least when nonpredictive social and non-social cues are involved and compared with each other. Under this view, different components of saccadic eye movements may be independently associated with the final attentional performance on manual RTs. Future research should aim at verifying whether these relationships may be the sign of independent contributions of these saccade parameters, in terms of cause-effect, on motor programming and execution of manual responses.

In this study I explored overt selection by examining the latency and landing position of initial saccades. However, in future studies other parameters may be evaluated to help expand the current results. For example, microsaccades (Engbert & Kliegl, 2003; Hafed & Clark, 2002; Valsecchi, Betta, & Turatto, 2007) may be a good source of information to study the dynamics of attention of individuals characterized by a low rate of eye movements. Specifically, in my case in Experiment 1 when the task was easy enough to be performed without involving any kind of saccades. One hypothesis that could be tested is that peak velocity and amplitude of microsaccades are affected by cue type just as saccades, showing a greater influence of the social cue on these parameters. However, since microsaccades are significantly affected by perceptual features of the stimuli (McCamy, Jazi, Otero-Millan, Macknik, & Martinez-Conde, 2013), a comparison between social and non-social cues would require a more systematic control of size and complexity in order to closely match the perceptual features of the two central cues.

My study suggests that it is possible to combine the analysis of the two components of orienting in one task and that this approach can help disclose links between overt selection and manual response. I pointed out how the eye gaze has an impact on latency that appears to persist until the final manual response. I also found a very strong association between validity effects on initial saccades and the magnitude of the final validity effect. My findings clearly point out the benefit of concurrently monitoring of eye movements in spatial cueing paradigms without explicit task instructions to make eye movements. My results support the idea that the systematic analysis of eye movements can help map the time-course and dynamics of cueing over time. This approach, together with a more precise characterization of the context in which orienting of attention occurs, could shed light on the debate regarding similarities and differences of social and non-social cues. This is of particular importance when I consider early profound deafness, where reorganizations of covert and overt orienting mechanisms as well as of face processing and susceptibility to social cues have been previously found. Therefore, in the next chapter I will illustrate the study I conducted to explore the interplay between covert and overt orienting of visual attention in response to social and non-social cues in profound deaf adults.

CHAPTER 3
CENTRAL CUEING IN EARLY PROFOUND DEAF ADULTS

The following chapter has been submitted in form of research article and it is currently under review:

Bonmassar, C., Pavani, F., Di Renzo, A., Caselli, M.C., & van Zoest, W. (under review). Eye movement patterns to social and non-social cues in early deaf adults. *Quarterly Journal of Experimental Psychology*

3.1 Introduction

In the last decades, the study of deafness and its impact on cognition has gained increasing attention. Specifically, findings on the consequence of early deafness on vision have added evidence in favor of an "enhancement of the remaining senses" (cit. Proksch & Bavelier, 2002) such that visual and tactile processing is improved for deaf observers compared to hearing observers (for example, see Bavelier, Dye, & Hauser, 2006; Levänen & Hamdorf, 2001). As vision is often regarded as the dominant sense, most research investigating this hypothesis focuses on changes in visual processing. Deafness-related adaptations in visual attention and selection suggest that deaf individuals allocate more attentional resources to the periphery than to the central field (Bavelier et al., 2000; Bosworth & Dobkins, 2002; Dye & Bavelier, 2010; Parasnis, 1992; Parasnis & Samar, 1985; Pavani & Bottari, 2012; Proksch & Bavelier, 2002; Reynolds, 1993).

One question that remains unanswered is whether deafness-related alterations in covert attentional selection are directly related to changes in overt oculomotor performance. Previous research that has looked at oculomotor performance in deaf observers have primarily used explicit oculomotor selection tasks, such as the anti-saccade task (Bottari, Valsecchi, & Pavani, 2012) or visual search (Heimler, van Zoest, Baruffaldi, Donk, et al., 2015a). The aim of the present work was to investigate the contribution of overt eye movement performance to peripheral discrimination in the presence of social and non-social central cues. If deaf observers are better at discriminating visual information in the periphery, this may have implications for the oculomotor system and the necessity of making eye movements in this special population.

3.1.1 Changes in covert orienting in deaf observers

Reorganization of the visual domain following early profound deafness does not seem to encompass all stages of visual processing (e.g., including sensation, perception, selection and response generation), but seems to target specifically selective processes (Bavelier et al., 2006). For example, studies on visual sensory thresholds, such as brightness and contrast, failed to show differences between deaf adults and hearing peers (Bosworth & Dobkins, 1999; Bross & Sauerwein, 1980; Finney & Dobkins, 2001), while research that focused on selective attention in profound deaf individuals revealed a redistribution of spatial attention towards the periphery as well as an enhancement of visual motion processing (Colmenero, Catena, Fuentes, & Ramos, 2004; Dye, 2016; Dye, Baril, & Bavelier, 2007; Lore & Song, 1991; Neville & Lawson, 1987; Proksch & Bavelier, 2002; Shiell, Champoux, & Zatorre, 2014; Stevens & Neville, 2006; for a review see Pavani & Bottari, 2012).

In a classic study of Proksch and Bavelier (2002) deaf and hearing participants were presented with a discrimination task, in which eccentricity and perceptual load were manipulated. The results demonstrated that deaf individuals showed enhanced processing of irrelevant peripheral distractors, suggesting that attentional resources were greater in the periphery. Yet, in the center of the visual field, the deaf group exhausted attentional resources at a lower load than the hearing group. This finding was interpreted as a sign of redistribution, rather than a simple general enhancement, of spatial attention as a result of early deafness. Similarly, it has been shown that early deaf individuals allocate more attentional resources in the periphery, paying the cost on the center of their visual field, rather than simply seeing better that their hearing peers (Dye, 2016). Altogether, these findings on covert attention suggest that the redistribution of attentional resources to promote processing in the periphery is a specific reorganization that follows early deafness; a strategy that may be adaptive in everyday life to compensate the lack of auditory input.

Interestingly, recent findings on covert orienting of attention in the deaf population suggest deaf young children are more sensitive to centrally presented eye-gaze cues (Pavani, Venturini, Baruffaldi, Caselli & van Zoest, 2019), but then learn to control this social cue more than other non-social cues in the course of life (Heimler, van Zoest, Baruffaldi, Rinaldi, et al., 2015b). In a gaze-cue task participants perform a discrimination task with a central schematic face, whose gaze direction is completely nonpredictive of the target location (Driver et al., 1999; Friesen & Kingstone, 1998; Ristic et al., 2002). Even though gaze-direction is not informative, results typically show that responses are facilitated by a valid gaze cue compared to a neutral or an invalid one. In Heimler et al. (2015b), groups of early bilateral profound deaf and age-matched hearing adults performed a peripheral discrimination task with nonpredictive central gaze cues displayed prior to target and distractor onset. Because faces and eyes convey important information of the surrounding environment during social interactions, the authors hypothesized that deaf adults would be more affected by a social stimulus, therefore showing a larger cueing effect than hearing adults. Contrary to their prediction, deaf participants presented with the gaze cue did not show a significant cueing effect in manual reaction time. However, in a new sample, both experimental and control groups showed the expected cueing effect for uninformative arrow cues, considered non-social stimuli. The authors argued that the ability of deaf adults to inhibit automatic orienting behavior to the social cue may help find a balance between maintaining spatial attention on faces during social interactions and monitoring the surrounding environment. Top-down mechanisms may interact with bottom-up processes to modulate reflexive orienting and prioritize face-to-face communication. Moreover, this ability appears to be acquired during development, as recent research on deaf children revealed remarkably larger cueing effects in this group compared to their hearing peers (Pavani et al., 2019). This change in attentional behavior, from great to reduced susceptibility to social central cues may be driven by subsequent maturation of the adult brain.

3.1.2 Changes in overt selection in deaf observers

Deafness-related reorganizations in visual selection are not limited to covert attentional orienting, i.e. orienting without eye movements. Modifications in overt selection as measured via eye movements have been observed in studies looking at oculomotor control in deaf observers (Bottari et al., 2012; Heimler, van Zoest, Baruffaldi, Donk, et al., 2015a; Prasad et al., 2015).

In a study of 2012, Bottari and colleagues reported alterations of balance between voluntary and reflexive rapid eye movements in a pro- and anti-saccade task. Deaf and hearing participants were asked to execute saccades based on instruction they received on a trial-by-trial basis: in a pro-saccade condition they had to reach the lateralized target with a rapid eye-movement (reflexive saccade) while in the anti-saccade condition they had to inhibit the reflexive movement to the target and execute a voluntary saccade to the opposite side of where the target appeared. The results showed that deaf participants, while exhibiting facilitation in the pro-saccade task, committed more errors and were slower in the anti-saccade task. This was considered a sign of an alteration in the oculomotor control that facilitates reflexive eye-movements in profound deaf adults and it is consistent with findings in the domain of covert attention showing rapid reorienting behavior (Colmenero et al., 2004; Parasnis, 1992; Parasnis & Samar, 1985). More recently, Heimler and colleagues (2015a) examined the time-course of overt selection in profound deaf adults using a modified visual-search task, where target and distractor saliency was manipulated to examine how deaf observers balance saliency-driven and goal-driven eye-movements. In this work it emerged that deaf participants were better able to avoid saliency-driven saccades than their hearing peers, supporting the idea that deafness does not necessarily lead to uncontrolled prioritization of salient events in the visual field (see also Sladen, Tharpe, Ashmead, Grantham, & Chun, 2005). Although the above described studies seem conflicting in their results regarding the influence of stimulus-driven biases in deaf observers, this inconsistency may arise because of the different demands of the tasks. While eye movements in the pro-saccade task involved automatic detection of the abrupt onset target, the visual search task required feature-based selection of a specific target and involved competition between target and distractor items. Hence, modifications of the oculomotor behavior in the deaf population appear to be task or load specific.

From the review of previous studies on visual attention and selection, it emerges that deafness-related changes in visual covert or overt attention are quite specific. Three specific findings from previous work lead to one and the same specific hypothesis and prediction. First, based on observations that deaf adults are better at discriminating objects in the periphery using covert attention, deaf observers may rely less on eye movements. Second, based on evidence that suggests that deaf adults focus primarily on the eye area of faces during sign language comprehension and face processing (see for example Emmorey et al., 2009; Watanabe et al., 2011), deaf observers may show enhanced fixation, in particular when presented with the social cue. Third, based on evidence that suggests that deaf are able to inhibit automatic shifts to social central cues, deaf observers may show enhanced inhibitory oculomotor control, especially in the presence of the social gaze-cue presented centrally. Based on this line of reasoning, enhanced attentional performance in the periphery in deaf observers may be related to a decreased reliance on eye movements in this group. As attentional performance in the deaf population might depend on whether attention is cued via a gaze cue or an arrow cue (Heimler et al., 2015b), using both social and non-social central cues provides a means to test the relationship between attention and eye movements in two different contexts.

To investigate this, I extend recent work where I combined covert and overt measures, i.e. manual RT and eye-movement components, in a typical attentional cueing task using social and non-social cues in a group of hearing adults (Bonmassar, Pavani, & van Zoest, 2019). In this work with hearing adults, I investigated the role of *spontaneous* eye movements in response to central cues to understand the contingency between eye movements and attention in the processing of gaze and arrow cues. I showed that spontaneous eye movements are present during a cueing task, even if they are neither required nor necessary to discriminate the target shape. Importantly, there was a very strong relationship between the landing position of the first eye movement following presentation of the target and the final validity effect in manual response time. Finally, manual RT were overall slower and the validity effect on RTs was greater in the presence of eye movements. Whether such interactions between overt selection and manual performance are present and may be modified as a result of early deafness is still unknown.

In the current experiment, I combine work of Heimler and colleagues (2015b) and my own (Bonmassar et al., 2019) in order to test the hypothesis that overt orienting in response to social and non-social cues in early profound deaf adults is different from that of hearing controls. By tracking the gaze of participants during the task, I expected to gain insight into whether the increased attentional control shown by deaf adults in response to the gaze cue consequently results in enhanced oculomotor control. In this case, I should observe less eye movements in response to the gaze cue compared to the arrow cue. Alternatively, it may be the case that deaf adults do make spontaneous eye movements in response to gaze cues during the task, but the faster temporal dynamics of these eye movements (see Bottari et al., 2012) may promote the discrimination of the peripheral target in a way that eliminates differences between valid and invalid trials on manual RTs.

3.2 Experiment

3.2.1 Methods

Participants

Two groups of participants took part in the study. Twenty-five early bilateral deaf adults formed the experimental group, aged 18-48 (M_{age} = 30.8 years old; SD_{age} = 7.4; hearing loss at least 70 dB in the better ear; no diseases linked to deafness; females = 13; all right-handed; education, $M_{education}$ = 14 years, $SD_{education}$ = 1.78). They were recruited by the personnel of the Italian national association for the deaf (ENS, Ente Nazionale Sordi, in Trento) and by ISTC-CNR researchers in Rome and were tested in two rooms at disposal in the centers. Twenty-five hearing adults aged 20-49 constituted the control group (M_{age} = 29.5 years old; SD_{age} = 7.4; females = 13; all right-handed; education, $M_{education}$ = 16.8 years, $SD_{education}$ = 2.3) and were recruited from the local university and non-university population and tested in the CIMeC laboratories in Rovereto. All participants had normal or corrected-to normal vision. The study was conducted in accordance with the principles expressed in the Declaration of Helsinki and written informed consent of each participant was obtained. The study was approved by the Ethical Committee of the University of Trento (Protocol n. 2016-029) and participants could choose between a reimbursement of 8 €/h per hour, a gadget or course credits for their participation.

An estimation of the effect size was calculated on the basis of previous work that has looked at covert central cueing with similar stimuli (Heimler et al., 2015b; experiment 1). Main effects of cue validity and cue-target stimulus onset asynchrony reported in Heimler et al. (2015b) had effect sizes respectively of η^2_p = .21 and η^2_p = . 58 and the interaction between validity and group had an effect size of η^2_p = .12. To obtain a desired statistical power of .9 for the main effects corrected for publication bias (Anderson, Kelley, & Maxwell, 2017) and with an alpha value of .05, a minimum sample size of eight individuals was required, while a minimum of fifty participants was needed to obtain the desired statistical power for the interaction validity x group. Hence, my sample of fifty observers was appropriate for testing these effects. Finally, in the work of Heimler et al. (2015b), cue condition (gaze vs. arrow cue) was a between-subject factor, while in the present work I decided to increase statistical power by using a within-subject factorial design. I also did not include the eyes-closed precue condition (Heimler et al., 2015b) to maintain the same number of trials in the gaze and arrow cue condition.

Stimuli

The experiment was run on a 23-inch Asus VG 236 LCD monitor (100 Hz; resolution 1920x1080 pixels) at CIMeC and on a 23-inch HP LCD monitor (60 Hz; resolution 1920x1080 pixels) at the ISTC-CNR in

Rome. Both were set up with a viewing distance of 60 cm. Stimulus presentation was controlled by an AMD Radeon Graphics FirePro V4900 graphics card and a NVIDIA Quadro K620 graphics card. Luminance values were set by means of a Minolta CS-100A luminance meter. The background color was set to black, with a luminance of 0.17 cd/m^2 (RGB: 0, 0, 0). A fixation dot, which served to perform the drift correction, was presented at the center of the screen at the beginning of each trial. It was chosen from the predefined fixation dots in Opensesame (Mathôt, Schreij, & Theeuwes, 2012; dot style: large-filled). The fixation dot, target, distractor and arrow stimuli were light grey (RGB: 198, 197, 203) with a luminance of 47 cd/m^2.

Target and distractor were two 90° rotated squares of 1° width (visual angle). The distractor was a whole diamond, whereas the target had a missing part, which could be the top or the bottom. The missing part was a triangle, whose height was one fourth of the total height of the diamond. They were placed at 11° from the center of the screen, while the face and the arrow were centered (respectively 7.22°x 11.46° and 2.74° x 1.25° width x height). All stimuli but the face were created using Opensesame. Specifically, the face was taken from a face database (Oosterhof & Todorov, 2008), and the two directional gaze images (gaze left and right) were created from the straight-ahead gaze using Photoshop. The experiment was scripted and run using Opensesame, together with the Pygaze library (Dalmaijer, Mathôt, & Van der Stigchel, 2014) and the Psychopy backend (Peirce, 2007, 2009) to synchronize the PC with the eye-tracker host-PCs (Opensesame version 3.1.6; Pygaze 0.6.0a21).

Procedure and Design

Participants sat on an adjustable chair in front of the monitor in a dimly lit room. A chinrest was placed on the desk to minimize head movements. Participants’ gaze was recorded during the experiment using an eye-tracker (SR Research Ltd.); an Eyelink 1000 Desktop mount was used at CIMeC, while an Eyelink 1000 Portable was brought to Rome. Both eye-tracking systems collected monocular gaze position at a sampling rate of 1000 Hz [1] from the left eye. A 5-points-grid calibration routine was required before starting each experimental condition, namely gaze and arrow cue conditions. In addition, another default calibration was set at the end of the third block in each experimental condition. Consequently, participants underwent a minimum of 4 calibration routines throughout the experiment, although additional calibrations could take place when necessary (e.g. poor recording or noisy data due to glasses or contact lenses reflection). Instructions of the experiment were written in Italian and combined with visual sketches. Moreover, a fluent signer of Italian Sign Language (LIS) was always present to provide information about the procedure to the deaf participants, who preferred it to written and spoken Italian.

Participants were asked to fixate the central fixation dot at the beginning of each trial and throughout each trial and to ignore the central cues because uninformative. Each trial began once the drift correction was successfully performed. Depending on the cue-type condition, a face with straight-ahead gaze or a horizontal line was displayed for 1000 ms. After the pre-cue display, a directional cue was presented and it would be either a face looking to the left or to the right side or an arrow pointing to the left or right side. The stimulus onset asynchrony, i.e. SOA, between the cue and target was randomized and it could be of 250 or 750 ms. Importantly, cues were not predictive of target location. On half of the trials the cue correctly indicated on which side the target would appear (valid trials), while in the remaining half of trials it pointed to the future distractor location (invalid trials). Cue-type condition was counterbalanced across participants, so that half of participants started with the gaze cue condition and then switched to the arrow cue and vice versa.

Participants were asked to indicate whether the target missed the top or the bottom part, independently of the side of the screen in which the target appeared, and to give the response as fast and accurate as possible (see Figure 4). Participants responded by pressing the ‘up’ or ‘down’ arrow buttons on the computer keyboard using the index and middle fingers of their dominant hand. In total, participants were presented with 32 practice + 320 experimental trials. Specifically, each cue-type

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[1] 6 hearing participants’ gaze was recorded at a frequency rate of 500 Hz instead of 1000 Hz.

condition consisted in 16 practice trials and 160 experimental trials divided in 5 blocks. Once a block was over, participants received feedback on their average reaction time (RT) and on their accuracy and were given the opportunity to take a break. Between one cue-type condition and the other, all participants completed a questionnaire aimed at collecting anamnestic information concerning deafness (for the deaf group) and linguistic background, reading habits and exposure to action games (see Table 1 for selected relevant information on deaf participants).

Deaf Participant	Age	Degree of deafness: Left ear	Degree of deafness: Right ear	Detection of deafness	Cause of Deafness	Hearing aids	Age at first exposure of Italian Sign Language (in years)
1	36	Profound	Profound	Between 2-4 year old	Ototoxic medications	yes; bilateral	32
2	34	Severe	Severe	At birth	Ototoxic medications	yes; bilateral	19
3	33	Profound	Profound	Between 2-4 year old	Congenital	No	31
4	20	Profound	Profound	At birth	Congenital	yes; bilateral	Native
5	40	Severe	Severe	Between 1-2 year old	Ototoxic medications	yes; bilateral	29
6	19	Severe	Severe	Between 1-2 year old	Fever	yes; bilateral	8
7	33	Profound	Profound	At birth	Congenital	No	Native
8	32	Profound	Profound	At birth	Ototoxic medications	No	3
9	25	Profound	Profound	Unknown	Congenital	No	6
10	25	Profound	Profound	At birth	Congenital	No	Native
11	37	Profound	Profound	At birth	Congenital	No	Native

12	35	Profound	Profound	At birth	Congenital	yes; bilateral	16
13	37	Severe	Profound	At birth	Congenital	yes; single	4
14	29	Profound	Profound	At birth	Congenital	No	Native
15	27	Profound	Profound	At birth	Congenital	No	Native
16	22	Severe	Severe	Between 1-2 year old	Ototoxic medications	No	4
17	27	Severe	Severe	At birth	Congenital	No	Native
18	28	Severe	Severe	At birth	Congenital	yes; bilateral	4
19	26	Profound	Profound	At birth	Congenital	No	1
20	39	Severe	Severe	At birth	Congenital	No	Native
21	41	Profound	Profound	At birth	Congenital	No	Native
22	18	Profound	Profound	At birth	Congenital	yes; bilateral	Native
23	29	Profound	Profound	At birth	Congenital	No	Native
24	29	Profound	Profound	At birth	Congenital	No	Native
25	48	Profound	Profound	At birth	Congenital	No	6

Table 1. Summary of relevant information on deaf participants acquired through the questionnaire.

Note. For the variable degrees of deafness, profound means a hearing threshold of >81 dB in that ear, severe means a hearing threshold of 61-80 dB in that ear.

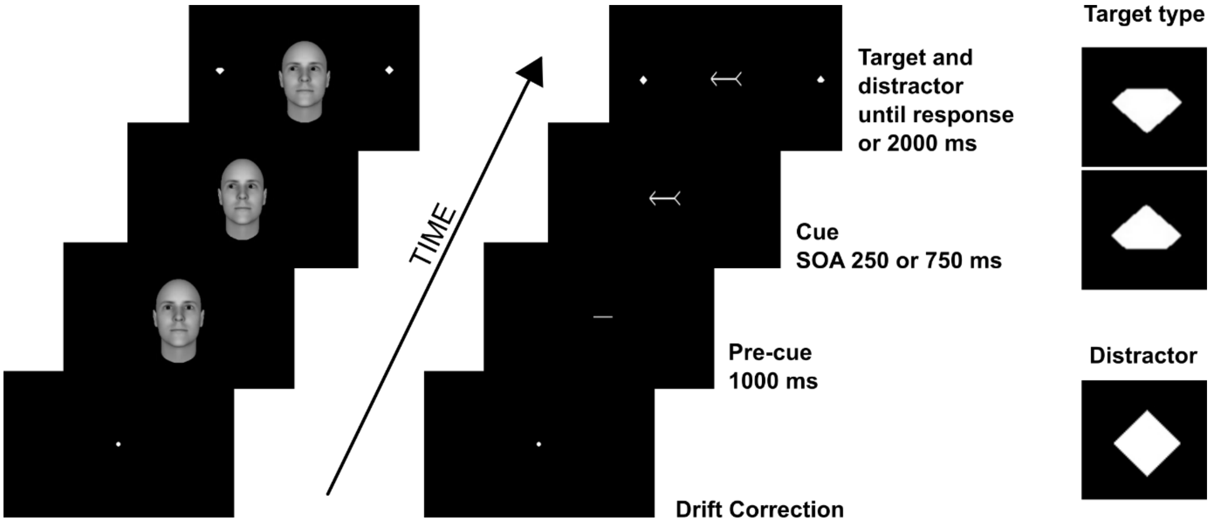

Figure 4. Trial sequence. On the left, stimuli (not in scale) used in the Experiment and the main trial sequence. Critically, both cues were nonpredictive of target location, i.e. they correctly indicated the future target location in 50% of trials. On the right, the target and distractor shapes are depicted.

3.2.2 Results

Analysis of both behavioral and eye tracking data was conducted with Matlab (The Mathworks; version R2016b), STATISTICA (Statsoft, Inc. 2004; version 7.0) and JASP (JASP Team, 2018; version 0.9.1.0, Windows 10). One deaf participant was excluded from the analysis because of very low attention span and one hearing participant was excluded because of noisy data that I was unable to correct by means of several re-calibrations.

The final data sets consisted in 24 deaf individuals (M = 31.3 years old; SD = 7.2; 13 females) and 24 hearing individuals (M = 29.9 years old; SD = 7.4; 13 females). A Student t-test was run to assess whether the two groups differed in age, but it did not highlight any differences $t(46) = .63$, p = .52. Conversely, the two groups differed in years of education (Mann-Whitney U test = 100, p < .001). Deaf adults had less years of education (*M* = 14 years, *SD* = 1.8) than their hearing peers (*M* = 16.8 years, *SD* = 2.3) [2].

Patterns of eye movements

Saccades were defined as rapid eye movements with velocities and accelerations exceeding 30°/s and 8000°/s^2. Only first saccades that were associated to correct manual responses were entered in the final analyses. Eye movements that were neither directed toward the target nor the distractor as well as eye movements with no landing coordinates were eliminated from the analysis. For each condition and group, less than 0.005% of trials was removed (Gaze-cue $_{\text{Deaf}}$ = 0.003%, Arrow-cue $_{\text{Deaf}}$ = 0.0009%; Gaze-cue $_{\text{Hearing}}$ = 0.005%, Arrow-cue $_{\text{Hearing}}$ = 0.003%). First, I examined the total frequency of eye movements for the two groups as a function of time. I observed two bimodal distributions for the two SOAs (Figure 5, panel A). In the short SOA, i.e. 250 ms, a first peak of eye movements developed within the range of 150 and 350 ms after the cue onset (median $_{\text{Deaf}}$ = 219 ms; median $_{\text{Hearing}}$ = 223 ms) and was followed by a second, higher peak with a median value of 420 ms in the deaf group and 407 in the hearing group. When the SOA was 750 ms, the first peak of eye movements after the cue onset had its median value respectively at 286 ms for the deaf and 266 ms for the hearing the second peak at 939 ms and 918 ms.

Based on the visual inspection of the distributions, I distinguished between cue-elicited eye movements, which were triggered by the cue present on the screen in isolation, from target-elicited eye movements, which followed the presentation of target and distractor. Irrespective of group and SOA, cue-elicited saccade distributions extended from 150 to 350 ms after the cue onset (see Figure 5, panel

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[2] I did not include education as a covariate in the analyses, as I did not have any a priori hypotheses on the role education may play with regard to orienting of visual attention in the deaf vs the hearing group. Previous studies did not report information concerning years of education of the samples, and to my knowledge, only one matched for years of education (Cattaneo, Cecchetto, & Papagno, 2016).

A). Conversely, to define the range of target-elicited eye movements I considered the two SOAs separately. In the short SOA, target-elicited saccades ranged from 100 ms after the target onset, while in the long SOA the distribution of eye movements started at 80 ms after target onset. To perform later analysis on the target-elicited saccades, I also set upper limits of the distributions using a 2 standard deviation from the mean criterion to remove outliers. Consequently, target-elicited saccades in the short SOA extended up to 779 ms for the deaf and up to 978 ms for the hearing adults and in the long SOA respectively up to 1234 ms and up to 1461 ms. After defining the ranges, I conducted separate analyses for the cue- and target-elicited distributions.

Overall proportion of eye movements

To compute total proportions of eye movements I divided the number of saccades executed by each participant by the number of trials left after removing incorrect, too fast and slow responses (see criteria described in the Behavioral data Section) and I transformed the values into percentages. With regard to cue-elicited saccade distributions, I noted that deaf and hearing participants behaved similarly. The gaze cue alone triggered saccades on 26% (SD = 19%) of trials in the deaf group and on 25% (SD =17%) in the hearing group, whereas the arrow cue triggered eye movements on 29% (SD = 19%) of trials in the deaf group and on 28% (SD = 18%) in the hearing group. I conducted paired samples Wilcoxon tests on the deaf and hearing sample to check for significant effects of cue type. The analysis did not reveal any significant differences neither between social and non-social cues in both deaf (W = 110, p = .26) and hearing (W = 126, p = .50) groups. Additionally, I compared the two groups on the average proportions of eye movements made, collapsed across cue type. The Mann-Whitney test did not reveal any group difference (W = 296, p = .88).

With respect to the target-elicited distributions, percentages revealed a remarkable difference between groups (see Figure 5, panel B). Deaf observers moved the eyes on average in 74% (SD = 35%) of trials in the gaze cue condition and 73.7% (SD = 34%) of trials in the arrow cue condition.

Conversely, oculomotor behavior varied dramatically across participants of the hearing group, as they responded overtly on 39% (SD = 38%) of trials in the gaze cue and 42% (SD = 40%) in the arrow cue condition. I repeated Wilcoxon tests for target-elicited proportions to test possible cue-driven effects but no difference emerged, neither in the deaf (W = 115, p = 1.0) nor in the hearing group (W = 142, p = .91). Finally, I compared the two groups on the average proportions of target-elicited saccades, collapsed across cue type. The Mann-Whitney test highlighted a significant group difference (W = 421, p = .01), in the sense that deaf observers executed significantly more eye movements.

The eye movement data was analyzed further only when participants provided sufficient data, that is, if at least 15 data points per cell were available in each combination of conditions (gaze vs. arrow & short vs. long SOA) (see also Bonmassar et al., 2019). Surprisingly, deaf participants revealed great consistency in their recruitment of eye movements during the task, as 20 out of 24 deaf adults systematically supported target discrimination with eye movements and met the criteria for sufficient eye movement data. Consequently, the deaf sample provided sufficient data points to perform analyses on saccade data. Conversely, only 9 hearing participants had enough data points to be entered in inferential statistical tests on eye movements. Consequently, the control data set appeared to be very noisy and based on the final inequality in sample size between the deaf and hearing group, statistical analyses on eye movements were conducted in the deaf sample only. Given that the sample size for the manual RT data were equal, the cue-effect on RT and accuracy between hearing and deaf groups were directly compared, including the full samples for both groups. Otherwise noted, datasets satisfied the assumption of normality and homogeneity of variances.

Behavioral cue-effect on RT

The overall accuracy rate was 98.5 % for the deaf adults and 98% for the hearing, therefore no further participants were excluded from the analyses. Incorrect responses, response times beyond 3 standard deviations from the average response time (RT) and timed-out trials were excluded from the final analysis. The total percentage of trials discarded from the analysis was respectively 2.26% for gaze cue condition and 2.41% for arrow cue condition in the deaf group and 3.25% for gaze and 3.23% for arrow cue condition in the hearing group. Mean response times were calculated and log-transformed to meet the assumptions of normality and equality of variances (Shapiro-Wilk normality test, all ps > .185; Levene's test, all ps > .06). RT data were entered into a mixed ANOVA with Group as between-subject factor and Cue, SOA and Validity as within-subject factors (see Figure 5, panel C). The group comparison revealed a reliable main effect of **Validity** across both groups (F (1, 46) = 36.937, p < .001, η^2_p = .44), **Group** (F (1, 46) = 7.943, p = .007, η^2_p = .15), **SOA** (F (1, 46) = 101.722, p < .001, η^2_p = .69). Valid trials resulted in faster response times (*M* = 704 ms, *SE* = 16.2) compared to invalid trials (*M* = 733 ms, *SE* = 18). Hearing adults (*M* = 670 ms, *SE* = 24) were overall faster at responding manually compared to deaf adults (*M* = 767 ms, *SE* = 24). Responses were faster to long SOA (*M* = 702 ms, *SE* = 17) compared to short SOA (*M* = 735 ms, *SE* = 17). There was no two-way interaction between Group and Validity (F (1, 46) = 2.52, p = .12, η^2_p = .05). Finally, a three-way interaction between **Cue, SOA and Group** (F (1, 46) = 4.791, p = 0.034, η^2_p = .094) was found and the post hoc comparisons with Bonferroni correction revealed that hearing adults responded faster to the gaze cue (*M* = 645 ms, *SE* = 25) compared to the arrow cue (*M* = 667 ms, *SE* = 25) in the long SOA condition. No other results were significant (all Fs < 2.591, ps > .12).

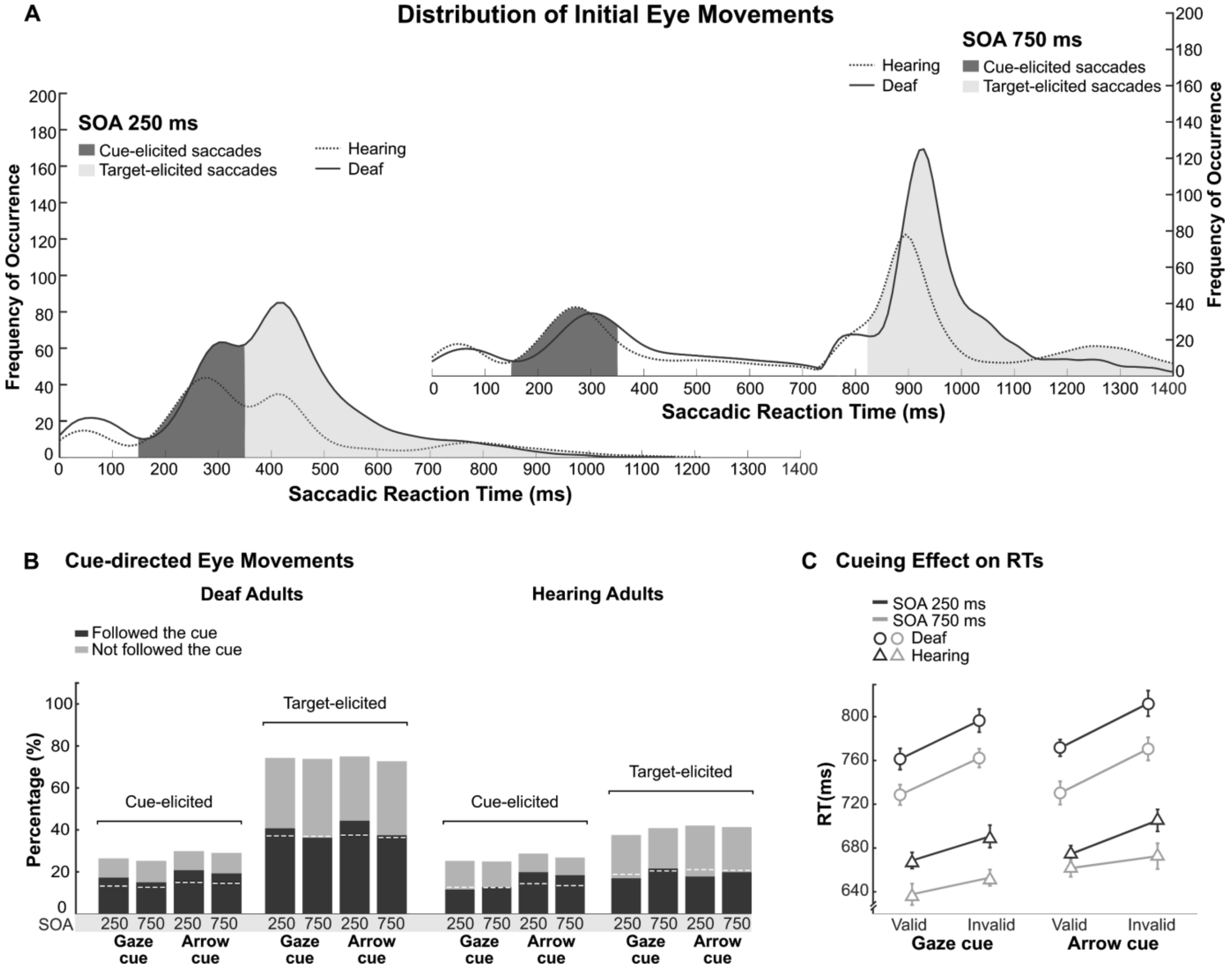

Figure 5. (A) Distributions of initial eye movements over time for both deaf and hearing groups, collapsed across cue condition. Deaf and hearing participants acted similarly in response to the cue in isolation (see total percentages of cue-elicited saccades), while they differed substantially once the target appeared. During the discrimination task, deaf observers relied significantly more on eye movements than their hearing peers, as indicated by the difference in peaks of target-elicited eye movements. **(B)** Mean percentages of cue-directed eye movements on short and long SOAs in gaze- and arrow cue conditions for all deaf and hearing participants. The white dashed line in each bar represents chance level at 50%. **(C)** Mean response times of correct responses to the target on valid and invalid trials for gaze- and arrow cue. For both groups, participants responded faster on valid trials than on invalid trials. Additionally, deaf participants responded overall slower compared to their hearing peers. Error bars represent within-subject standard errors, based on O’Brien & Cousineau, 2014.

Cue-elicited eye movements

Saccade direction. In this analysis, I included proportions of initial eye movements triggered by the nonpredictive cues presented in isolation, before the target onset. I computed percentages of eye movements that followed the direction indicated by the gaze and arrow cue. The results revealed that in the short SOA, deaf observers made eye movements in the direction of the gaze cue in 65% of all trials and overtly followed the arrow cue in 70% of all trials with eye movements. Similarly, in the long SOA participants followed the gaze cue in 60% and the arrow cue in 66% of the trials (see Figure 5, panel B). A repeated measures ANOVA on the percentages of cue-followed eye movements was performed to test whether the number of eye movements elicited in response to the cue depended on cue type, but no significant effect emerged (all Fs < 3.37, ps > .08).

Saccade latency. The dataset on latency included all initial saccades, whose latency was above the lower boundary, set at 150 ms. A 2x2 repeated measures ANOVA on the average saccadic reaction time was run, with Cue (gaze vs. arrow) and SOA (250 vs. 750 ms) as within-subject independent variables. A main effect of **Cue** F (1, 23) = 25.510, p < .001, η^2_p = .526 was found. Gaze cue condition triggered faster eye movements (M = 273.5 ms, SE = 3.6) than the arrow cue (M = 288.2 ms, SE = 3.9). No other main effects or interaction reached significance (all Fs < 0.059, ps > .811).

Target-elicited eye movements

Saccade landing position. To define the landing position and therefore the amplitude of initial saccades, I calculated the distance in degrees of visual angle between the x and y coordinates of the target center and the ending x and y coordinates of each saccade. A 2x2x2 repeated measures ANOVA was conducted on the average distance from the target in degrees of visual angle. Cue (gaze vs. arrow), SOA (250 vs. 750 ms) and validity (valid vs. invalid) were the within-subjects independent variables.

Main effect of **Validity** F (1, 21) = 26, $p < .001$, $\eta^2_p = .55$) was found. Valid trials (M = 8.62°, SE = 0.4) resulted in saccades landed closer to the target compared to invalid trials (M = 12.08°, SE = 0.6). Moreover, in the longer SOA both valid and invalid trials resulted in smaller eye movements, as shown by the two-way significant interaction between **Validity and SOA** F (1, 21) = 8.08, $p = .01$, $\eta^2_p = .28$). No other significant interactions were found (all $F < 3.2$ and $p > 0.086$). No main effect or interaction reached significance (all Fs < 1.40, ps > .25).

Saccade latency. Saccade latency was defined as the time between the target onset and the initiation of a saccade. The final dataset was log-transformed to meet the assumption of normality and entered a 2x2x2 repeated measures ANOVA on the average saccadic reaction time with Cue (gaze vs. arrow), SOA (250 vs. 750 ms) and validity (valid vs. invalid) as within-subject independent variables.

A main effect of **SOA** F(1, 21) = 31.3, $p < .001$, $\eta^2_p = .60$ was found, while the main effect of Cue was marginally significant, F(1, 21) = 3.8, $p = .06$ $\eta^2_p = .15$. In trials where the SOA was shorter, average saccade reaction time was longer (M = 250 ms, SE = 15.5) than in trials with longer SOA (M = 228 ms, SE = 13.4) (see Figure 6, panel A). No other main effects or interaction reached significance (all Fs < 2.04, ps > .17).

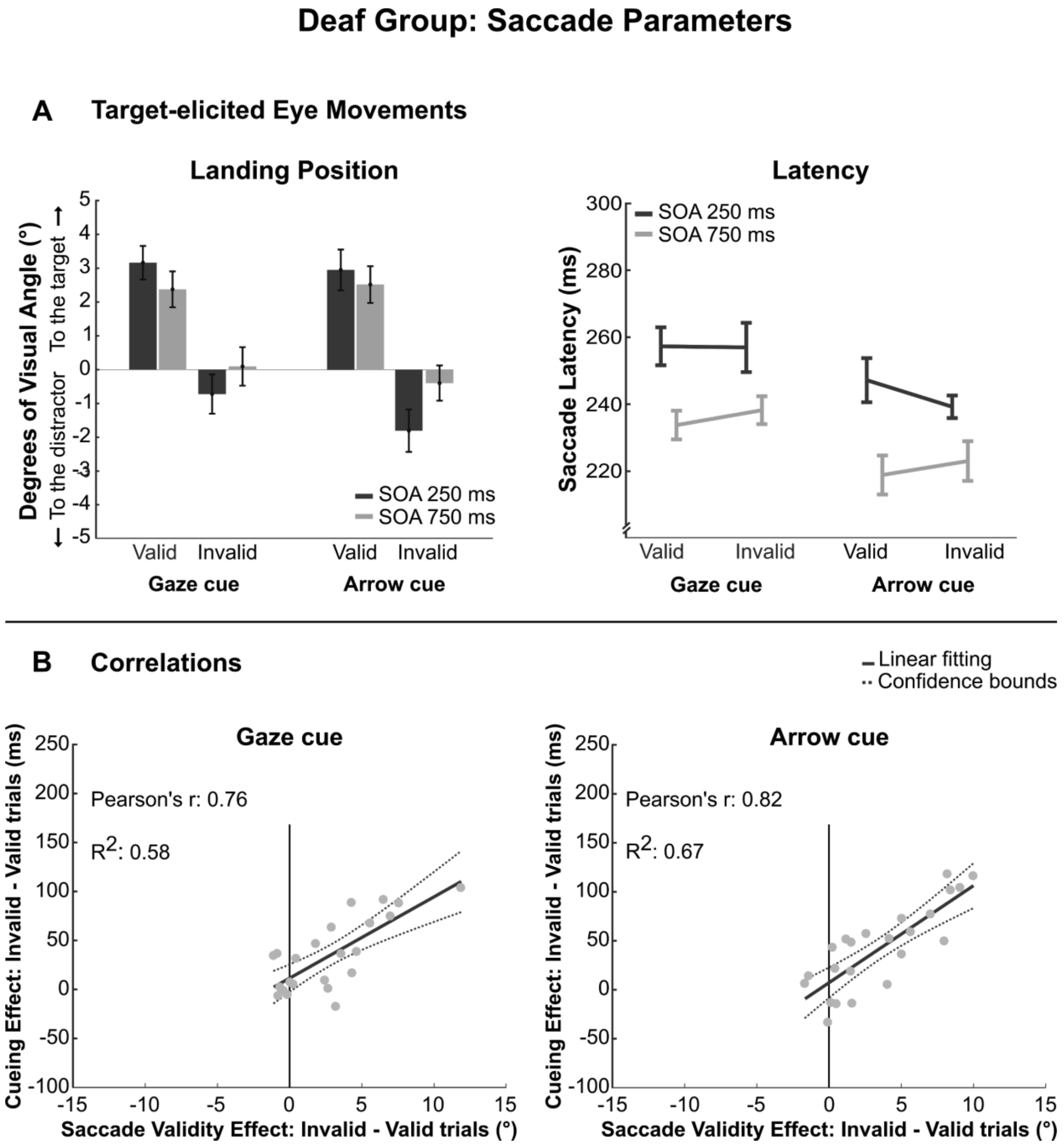

Figure 6. (A) Averaged target-elicited saccade landing positions on valid and invalid trials. On the y-axis, in degrees of visual angle, positive values represent saccades landed closer to the target and negative numbers indicate saccades landed closer to the distractor. On the right, mean onset latencies for target-elicited saccades on valid and invalid trials. While landing position was affected by validity, saccade latency was not. Error bars represent within-subject standard errors, based on O'Brien & Cousineau, 2014. **(B)** Correlations between validity effect on target-elicited saccades against cueing effect on manual RTs for gaze and arrow-cue conditions.

Correlations

To further investigate the relationship between oculomotor behavior and behavioral effect on manual RTs in the deaf sample, I plotted the validity effect on manual RTs against the validity effect on landing position of target-elicited saccades. Only trials where both RT and eye movement data were present were used to create the correlation plots. The validity effect on RT was computed by subtracting the average RT on valid trials from the one on invalid trials. Similarly, I computed the validity effect on target-elicited distance to target subtracting the values on valid trials from the corresponding ones on invalid trials. This procedure revealed the presence of strong positive linear correlations for both gaze, Pearson's *r*(23): .76, 95% confidence interval [.50, .89], $R^2 = .58$ and arrow cue condition, Pearson's *r*(23): .82, 95% confidence interval [.62, .92], $R^2 = .67$ (see Figure 6, panel B). The type of association indicates that the greater the difference in saccadic landing position in response to invalid and valid cues, the greater the difference in RT between invalid and valid cues.

Covariate Analysis

As I noticed that the hearing and deaf groups differed remarkably in terms of the number of eye movements made after the target onset, I also explored to what extent this characteristic influenced behavioral findings on RTs. In other words, does the fact that deaf make many more eye movements explain why they were overall slower responding? Following the procedure described by Schneider and colleagues (Schneider, Avivi-Reich, & Mozuraitis, 2015) to overcome typical issues of classification designs in ANCOVA analysis, I first checked whether the averaged percentage of eye movements was linearly related to the final manual RT. Furthermore, since the expected value of the covariate *Percentage of eye movements* was not similar across groups, I conducted the hybrid analysis proposed by Schneider and colleagues. Therefore I conducted the ANCOVA on the previous dataset adding also the centered covariate "Percentage of eye movements" and considered only main effect and possible interactions between the covariate and within-subject factors. Results highlighted the presence of an additional between-subjects main effect of **Percentage of eye movements** (F(1,45) = 15.65, $p < .001$, $\eta^2_p = .25$), and within-subject two-way interactions between **Validity and Percentage of eye movements** F(1,45) = 8.3, $p = .006$, $\eta^2_p = .16$, as well as between **SOA and Percentage of eye movements** F(1,45) = 5.9, $p = .02$, $\eta^2_p = .12$. The contribution of the covariate to performance was stronger in invalid trials than in valid trials but, crucially, did not vary as a function of group.

3.3 General Discussion

The present study showed at least three main important findings. First, deaf observers were overall much slower to respond in the manual task compared to the hearing observers. Second, there was no difference in the validity effect, showing that both the gaze and arrow cues influenced performance similarly in hearing and deaf observers alike. Third, while the proportion of cue-elicited eye movements were similar between hearing and deaf observers, deaf observers elicited nearly twice as many target-elicited eye movements compared to the hearing controls.

Regarding the first finding that deaf observers responded overall much slower, it is not uncommon to observe speed accuracy trade-offs in the visual abilities of deaf adults. These suggest that following deafness, modifications may occur at the level of response selection, but that these may also depend on task requirements. For example, prior findings in deaf observers have both documented a tendency to respond faster and to commit more errors in discrimination tasks (see for example Bosworth & Dobkins, 2002; Bottari, Nava, Ley, & Pavani, 2010), and also the reverse, the tendency to respond more slowly making fewer errors for more complicated tasks (see Heimler 2015a for oculomotor responses; Peressotti, Scaltritti, & Miozzo, 2018; Proksch & Bavelier 2002). This raises the possibility that a bias towards accuracy is more likely to emerge when a more difficult discrimination of stimuli in the periphery of the visual field is required. Much more than the hearing sample, my sample of deaf adults responded overtly during the target discrimination and this influenced the speed in manual performance (see covariate analysis). In deaf adults, the ability to inhibit automatic responses and to exert more cognitive control during response selection may occur at the expenses of speed. Evidence from prior vision research in deaf adults already highlighted that delays in the execution of voluntary saccades may serve an adaptive role, leading to more effective visual information processing when target-guided feature-based selection is needed (see Heimler et al., 2015a). This tight coupling between covert attention orienting and overt response in deaf adults may derive from the continuous monitoring of the environment through vision and the more extensive reliance on visual cues for spatial attention orienting. The concurrent need for accuracy in operating visual selection, which is of great importance in daily life to effectively interact with the environment, may slow down later stages of processing and response selection.

Second, the influence of nonpredictive social and non-social cues was evident in validity effects on manual reaction times and, importantly, for both hearing and deaf adults. Even though participants knew that both cues were uninformative of future target location, they responded faster to valid cues correctly predicting where the target would appear, and slower to invalid cues shown prior to target and distractor onset (see also Driver et al., 1999; Friesen & Kingstone, 1998; Ristic et al., 2002; Tipples, 2002). No differences between gaze and arrow cues emerged analyzing the magnitude of validity effects, supporting the hypothesis that the two cues trigger automatic orienting similarly (Stevens, West, Al-Aidroos, Weger, & Pratt, 2008). My work shows that attentional orienting in response to eye gaze was present in deaf adult observers and is similar to non-social orienting of attention.

Finding that deaf observers were overall much slower to respond, yet had the same absolute validity effect as their hearing peers, may suggest that the validity effect in the deaf sample was in fact an underestimation and possibly reduced relative to the hearing control group. In my previous work, I showed that slower overall RTs in a more difficult task were associated with an overall larger validity effect, which was likely mediated by an increase in the proportion of eye movements required in the more difficult task (Bonmassar et al., 2019). In the present study the validity effect in deaf observers did not reflect the fact that they were overall slower and required more eye movements.

In finding that deaf sample in the present study responded faster to validly cued target compared to the invalidly cued target I failed to replicate previous work suggesting that deaf are less sensitive to gaze-direction (Heimler et al., 2015b). There are several ways to explain this discrepancy. First, in the present sample, both the gaze- and arrow cue were presented counterbalanced within-subjects to increase statistical power. One possibility is that the within-subjects design mixed cueing-effects of deaf adults that were presented with the gaze cue in the first part, with those that responded to the gaze cue in the second part. Any reductions of the gaze-cueing effects may have disappeared because of the block-order randomization. Second, in the present sample, I measured eye movements. It may be the case that the simple presence of the eye tracker distinctly influenced the deaf observers to elicit more eye movements. An eye-tracking system may have inhibitory effects on people's natural looking behavior similar to an invasive social presence (Risko & Kingstone, 2011), but it remains an open question whether it can also boost eye movements in other situations and tasks, simply because participants are more sensitive to their eyes being monitored. Furthermore, prior findings indicate that people can be unaware of their looking behavior and the ability to explicitly report where they eyes moved often appears to be limited (see Belopolsky, Kramer, & Theeuwes, 2008; Clarke, Mahon, Irvine, & Hunt, 2017). Deaf adults may have been affected by the mere presence of the eye tracker without being fully aware of the subsequent intensification of their looking behavior.

Critically, deaf made many more target-elicited saccades compared to hearing observers, whereas deaf and hearing adults reacted similarly to the cues presented in isolation. This suggests that the presentation of the cue in isolation initially led to equal deployment of overt selection in both groups. In the presence of the target, the proportion of spontaneous eye movements in the hearing group confirmed that overt performance was not necessary nor required to perform the task accurately and only a subgroup of individuals responded overtly (see also Bonmassar et al. 2019). Nevertheless, deaf adults showed a great deployment of overt selection when target and distractor shapes were displayed, indicating that overt selection was the primary mechanism for almost all deaf observers in the group and was actively used to support discrimination of the target shape. The idea that deaf observers strategically used eye movement to benefit target discrimination, is supported by the results on landing position. The data on landing position revealed that target-elicited saccades landed closer to the target only on valid trials, while on invalid trials no bias was observed.

Finding that the deaf participants in the current sample are slower to respond overall, suggests that they are not better able to discriminate the targets in the periphery in this task. Finding that they require more eye movements, moreover suggests overt selection does not compensate for improved covert processing. If anything, the deaf observers did the opposite of what I predicted, as they were less quick to discriminate targets and required more eye movements during the discrimination.

Why are deaf observers making more eye movements? One could think that these are random eye movements without any precise purposes. Yet, this is quite unlikely to be the case, as I showed that validity effects on landing position and validity effects on manual RT were strongly associated in both cue conditions (see Figure 6, panel B). However, there are two possible ways to explain the correlation between saccadic landing position and the manual validity effect. First, it may be the case that the landing position guided the manual RT, such that because the eyes landed closer to the target, observers were able to respond more quickly to its identity. Given the differences in latency of the eye movement and the manual RT where the reaction of the eyes precede the manual response by on average half a second, this is a fairly plausible explanation (see also Bonmassar et al., 2019). Moreover, the quality of these eye movements - slow to elicit and landing closer to the target only - suggests that they were planned and executed to support the target discrimination and were not likely to be reflexive or random overt responses to stimuli appearing in the periphery of the visual field. This idea is in line with the view that eye movements help to determine manual performance.

Second, it may be the case that the eye movements and landing position are contingent on covert attentional selection that happens primarily in the cue-elicited phase. While cue-elicited performance was similar across deaf and hearing observers as well as the validity effect in RT, deaf observers may be less able to inhibit saccades in the direction of the target. This would explain why the percentage of target-elicited eye movements is so much higher in the deaf compared to the hearing group. This second explanation is related to the idea that there may be deafness-related changes in the interaction between covert attention and overt selection. In everyday life, these two mechanisms are coupled most of times in hearing individuals (Wright & Ward 2008; however, see Weaver, van Zoest, & Hickey, 2017), but deafness may in turn reinforce this coupling. When exploring a visual scene for example, evidence suggests that hearing participants rely more on parafoveal and peripheral vision than foveal vision to decide where to fixate next and to guide the search (e.g. Nuthmann, 2014). In profound deaf individuals, the reallocation of attentional resources to the periphery of the visual field may strengthen the coupling between covert orienting of attention to the periphery and subsequent execution of eye movements to better explore the environment. Under this view, the enhanced attentional resources to the periphery may trigger the oculomotor system in such a way that eye movements cannot be prevented during the discrimination of the target shape. Nevertheless, this does not translate to a greater validity effect on attentional performance, and again this could be explained by the idea that the covert attentional shift during the cueing phase determines the actual validity effect on manual responses.

Behavioral adaptations in visual attention and perception typically found in early profound deaf adults but not in deaf children support the idea that deafness-related changes occur slowly during development (Codina, Buckley, Port, & Pascalis, 2011; Dye & Hauser, 2014; Pavani et al., 2019). Additionally, maturation of the visual system throughout childhood as well as a gradual redistribution of visual attention to the periphery are further relevant factors that can account for inconsistent patterns between deaf children and deaf adults (Codina, Pascalis, et al., 2011). Prior research on deaf children suggests that initial disadvantages in vision can improve during development and progressively turn into enhanced visual attention abilities in the periphery of the visual field in adulthood. Similarly, while a preponderant effect of nonpredictive social cues on orienting of attention emerges in deaf children (Pavani et al., 2019), deaf adults show either the absence of it (Heimler et al. 2015b) or comparable effects with hearing peers and irrespective of cue type, as I report in my study. These findings are in line with the idea of slowly developing experience-dependent improvement in control of covert attention following early profound deafness.

A recent neuroimaging study looking at covert attention in profoundly congenitally deaf adults has shown that a network of cortical areas involved in attention, i.e. Posterior Parietal Cortex (PPC), Anterior Cingulate and Frontal Eye Field (FEF), exhibit augmented responsiveness to peripheral visual stimuli relative to a hearing control group (Scott, Karns, Dow, Stevens, & Neville, 2014). Furthermore, the activation of the frontoparietal network appears to be necessary to implement top-down attentional control, as goal-driven saccades are known to activate a frontoparietal network of brain regions (Corbetta & Shulman, 2002). Finally, animal models and the examination of patients with frontal lesions suggest that the FEF may exert inhibitory control on stimulus-driven saccade programming generated by the superior colliculus in favor of goal-driven saccade execution (Henik et al., 1994; Schlag-Rey, Schlag, & Dassonville, 1992). It remains an open question whether early deafness impacts this brain network of saccadic control beyond covert orienting of attention, possibly altering the interplay between these brain areas when executing eye movements or alternatively, altering the activation of parts of the network.

My sample of deaf observers revealed a heavy recruitment of eye movements during peripheral target discrimination. It may be hypothesized that the onset of the peripheral stimuli boosted the activity of the superior colliculus in deaf more than in hearing adults. Cortical areas like the FEF may in turn exert strong executive control over the superior colliculus in order to override reflexive orienting and favor prompt execution of voluntary saccades. This increased competition between parts of the network as well as greater activation patterns in both midbrain and cortical areas could explain why deaf adults are less able to prevent spontaneous eye movements when peripheral stimuli are displayed in this type of task. Finally, it is not unreasonable to think that such adaptations and neuroplasticity in frontal brain regions and in the attention network following early profound deafness occur during development, as children are known to show immature frontal lobes and less cognitive control (see for example Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002). Nevertheless, the deaf population can be quite heterogeneous when characteristics like communication preferences are considered (Dye & Bavelier, 2010). Therefore, future studies may further address whether and how social and linguistic experiences during the early sensitive linguistic period in development can shape visual attention in different ways from childhood to adulthood.

In conclusion, the current results suggest that deafness-related changes in the interaction between covert attention and overt selection are present in deaf adults. My data indicate that adapting modified visual abilities to task demands and prioritizing attentional control over reflexive orienting, may come at expenses of speed in later stages of response selection and may reveal an enhanced competition at a neural level between midbrain and cortical areas involved in the attention network.

Whether these signs of enhanced attentional control are unique features of early profound deafness, in the sense that they require a highly plastic brain and time to slowly and progressively develop, or they can be present in other forms of hearing loss and potentially emerge at different life stages, is still an open question. Effects of presbycusis at later stages in life may affect cognition and produce alterations in orienting of visual attention as well, which are still unknown. In the next chapter, I will describe in details the last study I conducted to examine possible changes in visual attention and in cognition following age-related hearing loss.

CHAPTER 4

CENTRAL CUEING IN OLDER ADULTS WITH AGE-RELATED HEARING LOSS

A research article based on the contents of this chapter is currently in preparation:

Bonmassar, C., Pavani, F., Spinella, D., Frau, G.N., & van Zoest, W. (in preparation). Is Attention deteriorated following Age-related Hearing Loss?

4.1 Introduction

In the course of life, one of the major factors driving structural modifications and changes in cognition is aging. Sensory functioning in vision and hearing can be impaired in older adults to various degrees, but decline affects also visual and auditory perception (Monge & Madden, 2016; Tun et al., 2009). Approximately one-third of individuals over 65 years are affected by presbycusis. As reported by the World Health Organization, "*It is likely that the number of people with disabling hearing loss will grow over the coming years. Projections show that the number could rise to 630 million by 2030 and may be over 900 million in 2050*" ("World Health Organization", 2018).

Recent studies have suggested that age-related hearing loss (ARHL), also known as pure presbycusis, may represent a potential risk factor for cognitive decline and Alzheimer disease. So far, an association between presbycusis and poorer cognitive performance has been highlighted, especially in neuropsychological tests that evaluate memory and executive functioning (Lin, Ferrucci, et al., 2011; Lin, Metter, et al., 2011). However, the understanding of this association is still limited and there is a dearth of evidence on the consequences of ARHL on other cognitive domains, like attention. Interestingly, the fact that impairments in selective attention are usually the first non-memory symptom in Alzheimer disease and are present also in amnestic MCI patients (McLaughlin, Anderson, Rich, Chertkow, & Murtha, 2014), points towards the need for a better characterization of attention in older adults with ARHL that are potentially at risk for cognitive decline. In the present study, I sought to investigate whether ARHL affects attention performance in older adults.

4.1.1 Aging: Orienting of attention

There are at least two different ways in which central cues can influence orienting of attention. Peripheral cues are typically flashes of light, which are presented for very short time and cause an involuntary (exogenous) shift of attention, while central cues are displayed at the centre of the screen, they last longer and are thought to induce a voluntary (endogenous) shift of attention most of times (Friesen & Kingstone, 1998; Jonides, 1981; Posner, 1978, 1980; Ristic, Friesen, & Kingstone, 2002; Tipples, 2008; Tipples, 2002). The impact of aging on attentional orienting seems to differ for peripheral compared to central cues. However, results are mixed. It has been reported that aging does not hamper exogenous orienting in response to abrupt-onset peripheral cues, even though in some cases longer facilitation effects of peripheral cues have been documented in older adults (e.g. Faust & Balota, 1997; Langley et al., 2011; however see Olk & Kingstone, 2015). Conversely, aging may negatively affect the efficiency of endogenous shifts of attention to the portion of space predicted by valid symbolic cues (e.g. Brodeur & Enns, 1997; Folk & Hoyer, 1992; Iarocci, Enns, Randolph, & Burack, 2009; Kingstone et al., 2002; Langley, Friesen, Saville, & Ciernia, 2011; Tales, Muir, Bayer, & Snowden, 2002; Waszak, Li, & Hommel, 2010; see Erel & Levy, 2016 for a review). With respect to central cues, it seems that validity effects are not affected by age when cues are presented in isolation, whereas the ability to voluntary orient attention worsens when they are competing with peripheral cues and inhibition is necessary (Bojko, Kramer, & Peterson, 2004; Iarocci et al., 2009; Tales et al., 2002). Nevertheless, some studies have reported no differences between older and younger adults (Curran, Hills, Patterson, & Strauss, 2001; Kingstone et al., 2002; Olk & Kingstone, 2015) in volitional orienting of attention. Olk and Kingstone (2015) argued that methodological approaches of previous studies failed to obtain consistent results because they did not isolate voluntary from involuntary shifts of attention. Specifically, in previous studies (Olk, Cameron, & Kingstone, 2008; Ristic & Kingstone, 2006), predictive arrow cues instantiated both voluntary and involuntary shifts of attention, therefore mixing the two components. Consequently, the study of pure volitional orienting should use central number cues that do not trigger unintentional automatic cueing of attention and probes only strategic, voluntary attention. In their task, Olk and Kingstone (2015) presented older adults with nonpredictive and predictive peripheral, central arrow and number cues to assess all possible combinations of involuntary and voluntary orienting. The nonpredictive arrow condition, which should reflect involuntary orienting to central cues, yielded a larger cueing effect in older adults, even when general slowing effect was controlled by means of standardized values. The researchers found an age-related difference only in the nonpredictive arrow cue condition, but not in the other predictive central arrow and number cue condition. In sum, this work demonstrates that older adults are comparable to younger adults in shifting attention in response to peripheral and central cues, both in a reflexive and a voluntarily and strategical manner, but voluntary orienting may be compromised by additional cognitive demands, like concurrent inhibition of automatic responses toward nonpredictive peripheral cues.

4.1.2 Aging: Social and non-social cues

Interestingly, an ability that seems to decline with age is the capacity to process social cues (Slessor, Laird, Phillips, Bull, & Filippou, 2010; Slessor, Phillips, & Bull, 2008). Eye-gaze processing and following is fundamental in establishing and engaging in joint attention with others and represents a critical aspect in social functioning (Langton & Bruce, 1999; Langton, Watt, & Bruce, 2000). As a result of inappropriate social communication and decline in representing mental states, emotions and intentions of others, older adults often experience social isolation (Phillips, MacLean, & Allen, 2002; Slessor, Phillips, & Bull, 2007; Sullivan & Ruffman, 2004), but only few studies have examined basic aspects of social perception like the ability to follow other people’s gaze and engage in joint attention. In 2008, Slessor and collaborators asked younger and older adults to detect subtle differences in eye-gaze direction. The results showed that older adults made more errors than younger adults in correctly identifying the eye-gaze direction when gaze aversion was subtle; critically, this finding was not explained by visual impairments or decline in visual contrast sensitivity. In addition, the ability to strategically orient attention in response to social and non-social cue was examined through a cueing task, in which central cues were valid on two third of trials. Results on RTs indicated that older adults followed both social and non-social cues but the magnitude of the cueing effect was reduced in this group compared to the younger adults. This finding was interpreted as a sign of decline in the strategic control of visual attention.

With respect to nonpredictive cues, Langley and collaborators (2011) examined orienting in response to uninformative arrows and found congruency effects in all groups, irrespective of age. Uninformative neutral schematic faces were used by Gayzur and colleagues (2014) to test processing of social cues and reflexive orienting in young, young-old (60-74 yrs) and old-old (75-91 yrs) participants. Their results demonstrated that in almost all cases validity effects in response to the gaze-cue were comparable in magnitude and time-course across age-groups. Only at short SOA (100 ms) and when the cue remained on the screen with the target, old-old adults did not show the cueing effect. Considering this pattern of results, it appears that reflexive orienting to social and non-social cues is mostly preserved later in life, although subtle modifications may occur. More recently, Slessor and colleagues (2016) extended their previous work testing the effects of nonpredictive gaze- and arrow-cues on attentional orienting in older adults. Contrary to Gayzur and colleagues (2014), they used pictures of real faces as gaze cues. Older adults showed reduced cueing effect also when the gaze cue was nonpredictive of target location, suggesting that automatic orienting to uninformative social cues may be affected by age. The examination of benefits and attentional costs calculated in a second experiment using predictive eye-gaze cues revealed that older adults processed eye-gaze less efficiently than younger adults. Notably, the strength of the congruency effect in response to arrow cues was comparable between the two groups. These results may add evidence in favor of a specific social impairment in the processing of eye-gaze direction in older adults and support other findings showing difficulties in processing social information and emotional expression (Slessor et al., 2008; Sullivan, Ruffman, & Hutton, 2007; however see Smith et al., 2018).

Of note, there may be possible modulations of the cueing effect as a function of different types of gaze cues. Although work on younger adults have not highlighted relevant distinctions, differences in the processing of schematic vs. natural faces seem to emerge for older adults. If present, impairments in gaze-processing may negatively affect social functioning of older-adults, selectively undermining the ability to engage in joint attention and facilitating communication with others. This point is of particular interest given the current focus on age-related hearing loss. Presbycusis hampers social interaction (Lin, Ferrucci, et al., 2011; Lin, Metter, et al., 2011; Mick, Kawachi, & Lin, 2014) and appears to be associated with cognitive decline. Hence, it will be important to determine the impact of presbycusis on basic social perception abilities such as eye-gaze processing and following.

4.1.3 Age-related hearing loss and cognition

In an attempt to recognize cognitive decline and neurodegenerations in the early stages, recent research has started focusing on the impact of presbycusis on cognitive functioning in older adults. In a meta-analysis, Loughrey and collaborators (2018) have sought to determine the strength of the association between ARHL, cognitive functions and cognitive decline. Associations between ARHL and decline are found in multiple domains of cognition, such as fluency, executive functions, semantic memory, visuospatial abilities and processing speed. Other factors like depression may exert an influence on attentional abilities. Nevertheless, causal mechanisms explaining these associations are still unclear and several hypotheses on the relationship between deafness, blindness and cognitive decline have been proposed (see Roberts & Allen, 2016; Schneider & Pichora-Fuller, 2000). According to the *cognitive load on perception hypothesis* (Lindenberger & Baltes, 1994), cognitive decline may lead to poor performance on auditory perception tasks because it reduces cognitive resources at disposal. Conversely, the *sensory-deprivation hypothesis* rather sees presbycusis as the casual factor of cognitive decline (Lin et al., 2013; Lindenberger & Baltes, 1994), whereas for the *information degradation hypothesis* presbycusis impoverishes cognitive performance but the condition can be reversible to some extent (Schneider & Pichora-Fuller, 2000). Finally, the *common cause hypothesis* considers a third external common factor as the one causing both presbycusis and cognitive decline, e.g. cerebrovascular diseases (Baltes & Lindenberger, 1997).

More recently, Wayne and Johnsrude (2015) have examined the amount of evidence in favor of each of these hypotheses focusing on cognitive decline and presbycusis only, rather than sensory impairment in general. It emerges that of the four hypotheses outlined, the common cause hypothesis and the sensory hypothesis (the combination of the information-degradation and sensory-deprivation hypotheses) have received the most scientific support. Nevertheless, a framework that integrates the strengths of the two hypotheses together with other factors moderating or modulating the impact of presbycusis on cognition may help conceptualize this complex relationship. In fact, factors like cognitive reserve and social isolation may also play an important role (Lin, Metter, et al., 2011; Mishra, Stenfelt, Lunner, Rönnberg, & Rudner, 2014; Rudner & Lunner, 2013). Cognitive reserve reflects individual variability in the processing capacity of information and it has been shown that individuals with greater cognitive resources can cope better with difficult auditory perception. Social isolation derives from communicative impairments due to presbycusis and it is associated with poorer cognitive function in older adults (Shankar, Hamer, McMunn, & Steptoe, 2013; Strawbridge et al., 2000). Furthermore, it is important to take into account that intervention through early diagnosis and treatment by means of hearing aids may be beneficial to short-term and semantic memory in older adults with cognitive decline (Castiglione et al., 2016; Fortunato et al., 2016; Hubbard, Mamo, & Hopper, 2018; Servidoni & Conterno, 2018).

Alternatively, it may be possible that a compensation and enhancement of other sensory-related mechanisms, such as visual attention, occurs to some extent in older adults suffering from ARHL and remains specific to the attention domain. So far, this topic has been mainly addressed in the study of early profound deafness and blindness (see for example Bavelier, Dye, & Hauser, 2006; Collignon & De

Volder, 2009; Proksch & Bavelier, 2002; for reviews see Fine & Park, 2018; King, 2015; Pavani & Bottari, 2012), showing that sensory compensations in the intact remaining sense are present and seem to be the product of a progressive reorganization taking place during development (for early deafness see e.g. Dye & Bavelier, 2010; Dye & Hauser, 2014; Pavani, Venturini, Baruffaldi, Caselli, & Zoest, 2019). In the case of congenital profound deaf individuals, redistribution of visual attention from the center to the periphery has been documented in deaf adults (Bavelier et al., 2000; Dye, 2016; Dye, Hauser, & Bavelier, 2009; Proksch & Bavelier, 2002) and serves an important adaptive role in everyday life to better monitor the environment in the lack of auditory inputs. Not only peripheral visual attention appears to change following early deafness: other aspects of attention, e.g. face processing and orienting of attention in response to socially relevant stimuli like faces and eye-gaze is also subject to change following early deafness (Benetti et al., 2017; Heimler, van Zoest, Baruffaldi, Rinaldi, et al., 2015). Recent studies with early profound deaf children and adults have pointed out how attentional control may improve thanks to experience-dependent plasticity, shifting from enhanced salience for social cues in children to substantial reduction of this cues in deaf adults, presumably to optimize social communication and interaction (Bonmassar, Pavani, Di Renzo, Caselli & van Zoest, submitted; Benetti et al., 2017; Heimler et al., 2015b; Pavani et al., 2019). Whether such a reorganization of attention following age-related partial hearing loss occurs is still unknown.

From this brief review on attention, ARHL and aging, it emerges the need for a better characterization of the changes in visual attention at later stages of life, with a particular focus on the consequences of presbycusis on cognition. Examining the possible modifications of attention and visual cognition in older adults is particularly interesting, as it can help tease apart the effects of presbycusis from the consequences of aging on visual attention.

In the current experiment, I take advantage of two well-known experimental paradigms, i.e. the Spatial cueing task (Posner, 1978, 1980) and the Eriksen Flanker task (Eriksen & Eriksen, 1974), to test the hypothesis that ARHL affects non-linguistic domains of cognition, such as covert orienting of attention, processing of social cues, selective attention and inhibition. The spatial cueing paradigm has been widely used to examine attention orienting to central cues. Typically, participants are presented with a central cue (arrow, eye-gaze, fingers pointing, etc.) indicating the left or the right side of the screen and are instructed to respond to a target appearing at previously cued- or uncued-locations, while maintaining fixation at center. Manual RTs are faster for targets appearing at cued locations relative to those appearing at uncued locations. The flanker task serves to test inhibition of task-irrelevant information. In this paradigm, a central target (a letter on an arrowhead) is flanked by irrelevant distractors (flankers) on the left and on the right. The flankers can have the same target identity or orientation (congruent condition), or can be different or have the opposite orientation (incongruent condition), or they may be neutral regarding the response. Manual RTs are normally slower and error rate increases in the incongruent compared to the congruent or neutral condition. The interference effect, obtained from the subtraction of congruent from incongruent conditions, is an index of the susceptibility to interference of irrelevant stimulus information.

If ARHL negatively affects cognition and attention in older adults, I expect to observe diminished attentional control; this would be evidenced by increased distraction and by greater cueing effects on RTs and increased interference effects in the Flanker task compared to typically hearing older adults. If ARHL results in an increased deficit in processing social stimuli and a presumably greater social isolation compared to typically hearing aging participants, I predict additional differences between social eye-gaze and non-social arrow-cue performance. This may lead to relatively reduced effect of the social eye-gaze on attention performance in the ARHL group. Alternatively, ARHL might instantiate increased sensitivity to available cues in the environment, as in the case of early profound deafness, and the ARHL might show a relatively increase in the gaze-cue effect but not the arrow-cue effect compared to their hearing peers. Finally, I predict worse overall cognitive functioning in the neuropsychological tests in the ARHL compared to the hearing sample.

4.2 Experiment

4.2.1 Methods

Participants

Two groups of participants took part in the experiment. Thirty-one adults >64 years diagnosed with bilateral symmetrical mild to moderate presbycusis formed the experimental group, aged 64-79 years old. Eighteen older adults had a bilateral mild presbycusis between 26-40 dB in the better ear, while other 13 suffered from a bilateral moderate presbycusis (41-60 dB in the better ear). They were recruited by the personnel of the Otolaryngologist ENT Unit in Rovereto (Italy). Eighteen age-matched adults >64 without presbycusis constituted the control group and were recruited from the local population. Descriptive statistics of the two groups and raw scores for the tests used are reported in Table 2. All participants were tested at the Center for Neurocognitive Rehabilitation (CeRiN, University of Trento) in Rovereto. All participants had normal or corrected-to normal vision. Moreover, informed consent of each participant was obtained and the study, which was approved by the Ethical Committee of the University of Trento, was conducted in accordance with the principles expressed in the Declaration of Helsinki. Participants could choose between a reimbursement of 8 €/h per hour or gadgets for their participation. An estimation of the effect size was determined by considering previous work that examined covert attention using similar central cues (Heimler et al., 2015, experiment 1). In the study of Heimler and colleagues (2015), main effects of cue validity had an effect size of $\eta^2_p = .21$ and cue-target stimulus onset asynchrony of $\eta^2_p = .58$. To reach a desired statistical power of .9 for the main effects corrected for publication bias (Anderson, Kelley, & Maxwell, 2017) and with an alpha value of .05, a minimum sample size of eight individuals was needed. Hence, my samples were appropriate for testing these effects.

Stimuli

The experiment was run on a 23-inch HP LCD monitor (60 Hz; resolution 1920x1080 pixels) at viewing distance of 60 cm from participants' eyes. Stimulus presentation was controlled by a NVIDIA Quadro K620 graphics card. Luminance values were measured with a Minolta CS-100A luminance meter. The spatial cueing task and the Flanker task were programmed using OpenSesame, version 3.1.6 with Psychopy backend (Mathôt, Schreij, & Theeuwes, 2012; Peirce, 2007, 2009).

In the spatial cueing task, the background colour was set to black, with a luminance of 0.17 cd/m^2 (RGB: 0, 0, 0). A predefined fixation dot was presented at the centre of the screen at the beginning of each trial. The fixation dot, target, distractor and arrow stimuli were light grey (RGB: 198, 197, 203) with a luminance of 47 cd/m^2. Target and distractor were two diamond shapes of 1° width (visual angle). The target shape differed from the distractor because its top or bottom part was missing (see Figure 7, panel A). The missing part was a triangle, whose height was one fourth of the total height of the diamond. Target and distractor appeared at 11° of eccentricity from the centre of the screen, while face and the arrow cues were centred (respectively 7.22°x 11.46° and 2.74° x 1.25° width x height). The face was imported from an existing database (Oosterhof & Todorov, 2008), and the two directional gaze images (gaze left and right) were obtained starting from the straight-ahead gaze using Photoshop.

In the flanker task the background colour was set to grey, with a luminance of 2.5 cd/m^2 (RGB: 72, 72, 72), while the target and distractor stimuli and lines were white (RGB: 255, 255, 255) with a luminance of 50 cd/m^2. The stimuli consisted in 5 stimuli (arrowheads or lines) placed in an imaginary horizontal row, whose total length was 9.7° degrees of visual angle. The target was at centre of the screen and was flanked by two pairs of distractors of the same size (1.32° x 1.58° width x height) or with lines of the same width (see Figure 7, panel B).

Audiometry. Older adults with bilateral pure presbycusis were categorized into the group with mild to moderate ARHL on the basis of a previously performed audiometric assessment in a sound-treated booth at the Hospital of Rovereto. Hearing thresholds in each ear were obtained from 500 to 4000 Hz with headphones using an audiometer (Madsen® Astera2, GN Otometrics). A pure-tone average of hearing thresholds at 500 to 4000 Hz was calculated for the better-hearing ear. Mild presbycusis was defined as an average hearing threshold ranging from 26 to 40 dB and moderate presbycusis comprised hearing thresholds between 41 and 60 dB, according to the medical definition of hearing loss provided by the World Health Organization. Hearing acuity testing for the control group was conducted using a portable screening audiometer (GSI 17, Guymark UK Ltd.), measuring pure-tone thresholds in each ear at 500, 1000, 2000, and 4000 Hz. Hearing acuity was determined as the average hearing threshold (in dB), for the better-hearing ear, averaged across the four frequencies.

Neuropsychological Tests

The *Montreal Cognitive Assessment* (MoCA) served as a cognitive screening instrument consisting of small paper-and-pencil tasks across different cognitive domains (Nasreddine et al., 2005), to check differences in cognitive functioning between groups. It consists of a 10-minute, 30-point test that emphasizes tasks of executive functioning and attention, resulting more sensitive in detecting mild cognitive impairment (MCI).

The *Attentive Matrices* (Spinnler & Tognoni, 1987) test visual search abilities and selective attention. The test consists of three different patterns of digits from 1 to 9 on three sheets. The participant’s task is to check the numbers to find a target number (from one to three digits) as quick as possible. All digits marked after 45’’ are not included in the final score. The maximum score is 60.

The *Trial Making Test* (TMT) is administered to test processing speed and divided attention (Reitan, 1958). In this test, circles containing digits (part A) or both digits and letter (part B) are distributed on two sheets. On the first sheet, the circles include only numbers (1–25) in random order and participants are asked to connect digits in ascending order as quickly and as accurate as possible. On the second sheet, both numbers (1–13) and letters (A–N) are displayed in random order and the participant's task is to connect digits and letters in ascending order and in an alternate fashion (1-A-2-B-3-C, etc.). The final dependent variables are the time (in seconds) required to complete the tasks.

Additionally, the subtraction of the time needed to complete the first tasks from the second task is considered to reflect shifting time, a measure of switching ability.

The *Hearing Handicap Inventory for the Elderly* (HHI-E; Ventry & Weinstein, 1982) is a 25-item questionnaire, which aims at detecting functional negative effects resulting from presbycusis and the impact of hearing loss on psychological well-being. Given that the questionnaire presents a 13-item emotional subscale and a 12-item socio-situational subscale, it is possible to obtain a score of perceived handicap on both dimensions. The HHI-E global index has a maximum value of 100. Scores in the range 17-42 indicate mild to moderate hearing handicap, while scores ≥43 indicate a significant hearing handicap.

Procedure and Design

All tasks were performed during one session. In order to prevent biases in cognitive testing due to impaired hearing, the experimenter calibrated voice loudness at the beginning of the session and based on each participant's feedback. Throughout the session, instructions were given speaking slowly, clearly and loudly enough and participants were tested in a quiet room without ambient noise. Participants were first administered the neuropsychological tests, which comprised the MoCA, the Attentive Matrices and the TMT A and B. Hearing controls also performed a brief audiometry test in the same room. After this first part, participants were invited to sit on an adjustable chair in front of the PC monitor and the main lights were turned off, so that the room was dimly lighted. A chinrest was placed on the desk to minimize head movements. Task instructions were given in written and spoken Italian and combined with visual sketches.

In the spatial cueing task with uninformative social and non-social cues, participants were asked to fixate the central fixation dot at the beginning of each trial, to maintain fixation throughout each trial and to ignore the central cues because nonpredictive of target location. Cue-type condition was counterbalanced across participants. Depending on the cue-type condition, a face with straight-ahead gaze or a horizontal line was displayed for 1000 ms. After that, a spatial cue was presented and it consisted either in the face looking to the left or to the right side or in an arrow pointing to the left or right side. The stimulus onset asynchrony, i.e. SOA, between the cue and target was randomized and it could be of 250 or 750 ms. As said, cues were uninformative, meaning that in half of the trials the cue correctly indicated future target location (valid trials), while in the remaining half of trials it pointed to the future distractor location (invalid trials). Participants were asked to identify the missing part of the target, i.e. either the top or the bottom, by pressing the ‘up’ or ‘down’ arrow buttons on the computer keyboard using the index and middle fingers of their dominant hand (timeout of 3000 ms). They were asked to be as quick and accurate as possible (see Figure 7, panel A). Each cue-type condition consisted in 16 practice trials and 160 experimental trials divided in 5 blocks. At the end of each block, participants could take a break and received feedback on their average reaction time (RT) and on their accuracy. Between one cue-type condition and the other, all participants completed a questionnaire aimed at collecting anamnestic information concerning their health condition, linguistic background, reading habits and the presbycusis, if they suffered from it.

In the Flanker task, a fixation point lasted for 1000 ms to ensure participants’ fixation and was followed by the presentation of one centrally presented arrowhead pointing either to the left or to the right, which was flanked by further 4 arrowheads or horizontal lines with the same width. In the congruent condition flankers and target pointed in the same direction; in the incongruent condition flankers pointed in opposite directions compared to the target. In the neutral condition the flankers were lines. All three conditions were equally probable and presented in a randomized order. Participants were asked to identify the pointing direction of the target arrowhead and press the corresponding left or right keyboard buttons (left arrow and right arrow keys) as fast and accurate as possible. There were 216 trials in total, divided in 3 blocks of 72 trials each. One a block was over, participants could take a short break.

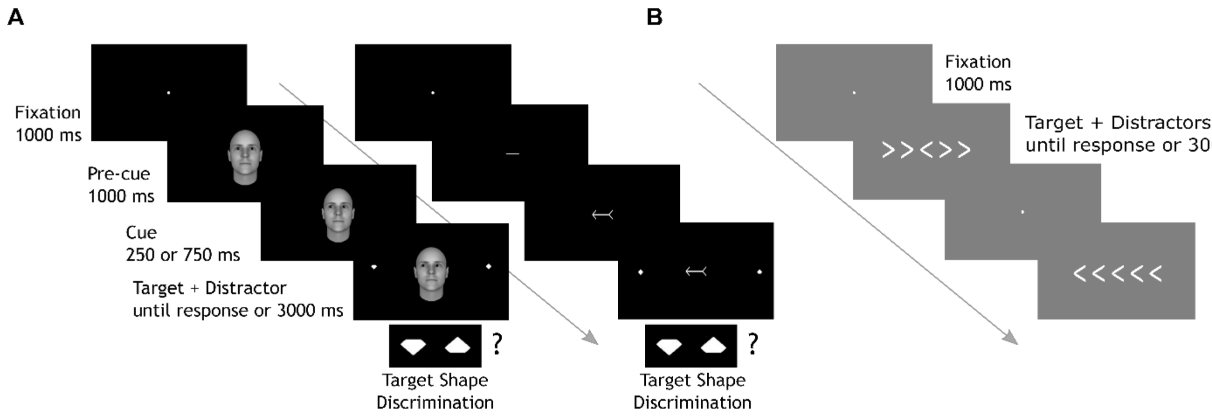

Figure 7. (A) Stimuli (not in scale) used in the spatial cueing task as well as main trial sequence. Target shapes used in the discrimination task are depicted. The distractor shape was always a whole diamond. **(B)** Stimuli and trial sequence of the Flanker interference task.

	Hearing Controls	Older adults with ARHL (26-60 dB)
	Mean (SD)	Mean (SD)
Samples	18	31
Age at Testing (years)	69.3 (3.3)	69.4 (3.8)
Gender, females	12 [67%]	19 [61%]
Education (years)	12.1 (3.1)	11.5 (4.3)
Hearing aids	--	13 (11 on both ears)
MoCA	26.7 (2.4)	25.1 (2.6)
Attentive Matrices	53.7 (4.7)	51.4 (5.9)
TMT A	37.8 (12.8)	44.3 (13.8)
TMT B	89 (36.2)	120 (47.8)
TMT B-A	51.2 (27)	75.7 (42.7)
HHI-E (global score)	--	24.7 (22.1)

Table 2. Clinical, educational data and results of neuropsychological evaluation of the samples. Raw scores of tests are presented in the table. Attentive matrices have a maximum score of 60, while TMT scores are expressed in seconds. HHI-E score has a maximum of 100 and scores in the range 17-42 indicate mild to moderate hearing handicap. ARHL, Age-related Hearing Loss; SD, standard deviation; MoCA, Montreal Cognitive Assessment. TMT, Trial Making Test; HHI-E, Hearing Handicap Inventory for the Elderly.

4.2.2 Results

Statistical analysis was performed using Matlab (The Mathworks; version R2016b) and JASP (JASP Team, 2019; version 0.10.2, Windows 10). Unless noted, datasets satisfied the assumptions of normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test).

Participants

Pre-existing differences between the two groups in terms of Age ($t = .08$, $df = 47$, $p = .93$) and Education ($t = .47$, $df = 47$, $p = .64$) were not present.

Spatial cueing task

The two groups performed well in the tasks, with an average accuracy rate of 98.7% for the hearing and 99% for older adults with mild to moderate ARHL. I excluded incorrect responses, response times beyond 3 standard deviations from the average response time (RT) and timed-out trials from the final analysis, so that the percentage of trials discarded from the analysis was respectively 1.88% in the hearing group and 1.73% in the group with mild to moderate presbycusis. Mean response times were calculated and log-transformed to meet the assumption of normality. A mixed ANOVA was carried out with Group as between-subject factor and Cue, SOA and Validity as within-subject factors (see Figure 8, panel A and B). Main effects of **SOA** ($F(1, 47) = 75.3$, $p < .001$, $\eta^2_p = .62$) and **Validity** ($F(1, 46) = 68.7$, $p < .001$, $\eta^2_p = .59$) were found to be significant across groups. The long SOA resulted in faster response times (*M* = 988 ms, *SE* = 16) compared to short SOA (*M* = 1016 ms, *SE* = 16) and valid trials produced faster responses (*M* = 977 ms, *SE* = 16) compared to invalid trials (*M* = 1018 ms, *SE* = 16). Interestingly, a two-way interaction between **Group and Validity** ($F(1, 47) = 4.13$, $p = .048$, $\eta^2_p = .08$) emerged. I directly compared the absolute magnitude of cueing effects in the two groups and it emerged that older adults with ARHL showed a reduced validity effect on RTs (*M* = 29 ms, *SE* = 7) compared to their hearing peers (*M* = 50 ms, *SE* =7). Two-way interactions between **Cue and SOA** (F (1, 46) = 9.98, p = .003, η^2_p = .17) and **Cue and Validity** (F (1, 46) = 6.95, p = .01, η^2_p = .13) were also found to be significant. Post-hoc tests with Bonferroni correction were carried out to further examine these interactions. The tests on the interaction between Cue and SOA revealed that the non-social cue (arrow) slowed RT especially in the short SOA. The analysis on the interaction between Cue and Validity pointed out that the non-social cue led to slower responses compared to the social cue when it was invalid. Finally, the interaction between Group, Cue and Validity was not significant, F (1, 47) = .4, p = .53, η^2_p = .008. No other results were significant (all Fs < 2.88, ps > .09).

Flanker task

As for the previous task, I calculated overall accuracy (hearing group = 98.5%; mild to moderate ARHL group = 98.8%). Raw RTs were pre-processed similar to those of the cueing task to remove outliers and errors (trials discarded in the hearing group = 3.06%; in the group with ARHL = 2.7%) and log-transformed to meet assumption of normality. Because sphericity assumption was violated (Mauchly's Test W = .65, p < .001), the Greenhouse-Geisser correction was applied to the mixed ANOVA with Group as between-subject factor and Congruency as within-subject factor (see Figure 8, panel C). The analysis revealed the main effect of Congruency only (F (1.415, 69.68) = 158.8, p < .001, η^2_p = .77). No further interactions or main effects were significant (all Fs < 1.02, ps > .32).

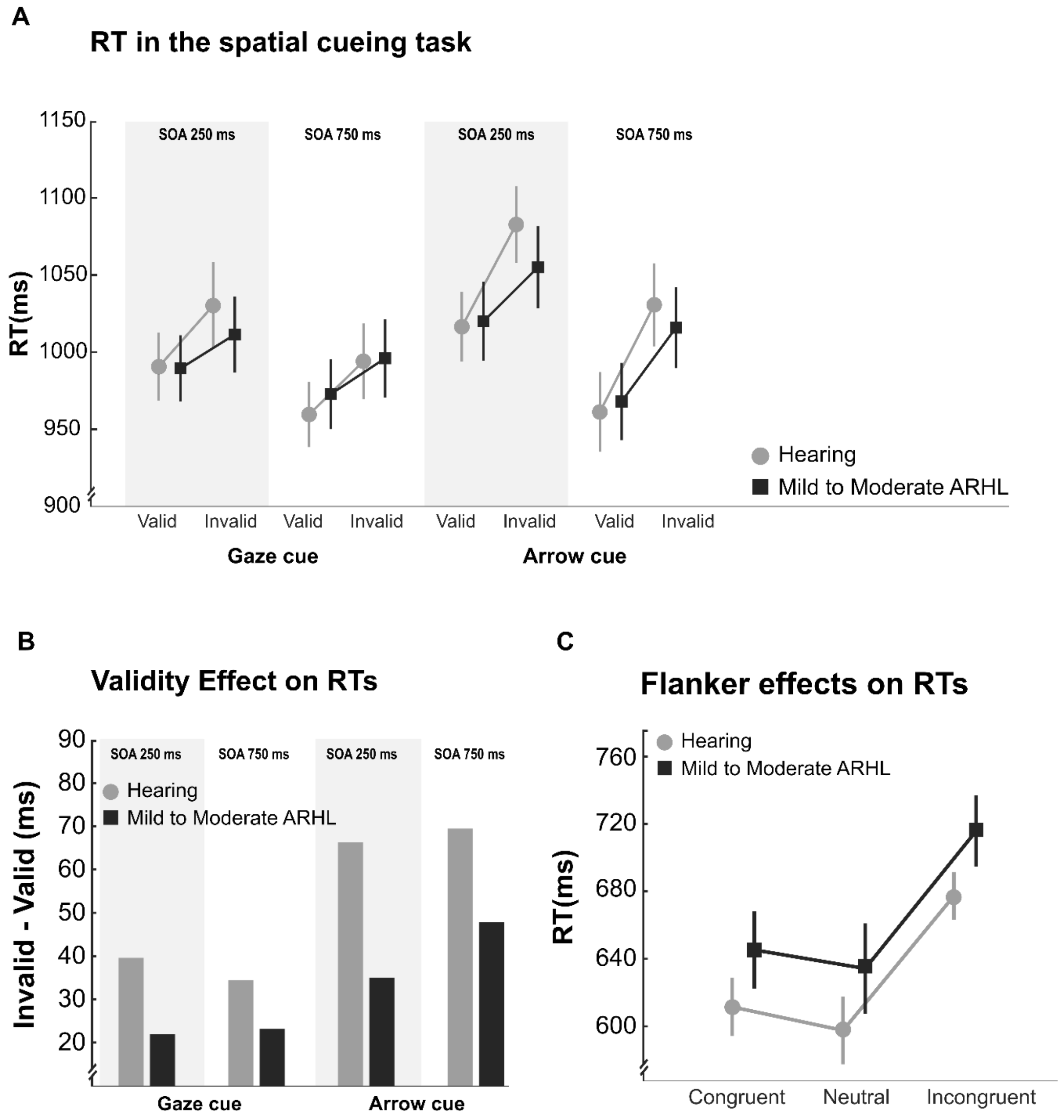

Figure 8. (A) Mean response times of correct responses to the target on valid and invalid trials for gaze- and arrow cue conditions in the two groups of interest. All error bars denote standard errors. **(B)** Validity effects on RT in the spatial cueing task, calculated as the difference in RTs between invalid and valid trials, in older adults with and without presbycusis. **(C)** Mean response times of correct responses to the target on congruent, neutral and incongruent trials in the Flanker Interference task and in the two groups of interest. All error bars denote standard errors.

Neuropsychological assessment

Mann-Whitney tests on raw scores of the selected neuropsychological tests were carried out to assess global cognitive functioning, attention and shifting capacities in the two groups. For the MoCA test, a significant difference between groups was found (W = 393, p = .02, $\mathbf{r_{rb}} =$ .41). TMT part A was marginally significant (W = 186, p = .05, $\mathbf{r_{rb}} =$ - .33). Main effect of Group was significant in TMT part B (W = 164, p = .02, $\mathbf{r_{rb}} =$ - .41) and TMT B-A (W = 178.5, p = .38, $\mathbf{r_{rb}} =$ - .36). The Attentive Matrices did not reveal any modulations (W = 341, p = .20, $\mathbf{r_{rb}} =$ .22). Results suggest that older adults with ARHL had worse global cognitive functioning and performed worse in tasks requiring divided attention and attentional shifting than peers without presbycusis.

Perceived hearing disability

Finally, I examined the perceived hearing handicap index obtain through the HHI-E of participants as a function of hearing loss. I divided the experimental group into a subgroup of individuals with mild presbycusis (n =18) and a subgroup with moderate presbycusis (n = 13). The Mann-Whitney test highlighted a significant difference between groups, with a perceived greater hearing disability in the subgroup with moderate presbycusis (W = 29.5, p = < .001, $\mathbf{r_{rb}} =$ -.75). I further plotted the indexes obtain from the questionnaire for whole group of participants with ARHL as a function of pure-tone hearing thresholds. A strong positive correlation between the perceived disability and the average hearing threshold of participants was found (*r* = .58, p < .001), indicating that perceived hearing handicap tended to increase together with the gravity of presbycusis.

4.3 General Discussion

The present study sought to investigate the effect of age-related hearing loss (ARHL) on attention and to what extent potential influences of acquired deafness can be isolated from general age-related modifications in performance. The results show that while some aspects of attention maintain preserved, other aspects of attention and cognition are affected by ARHL. First, my data indicate that the experimental and control groups were comparable in terms of overall response speed, suggesting that presbycusis is not associated with an additional worsening in general processing speed. This aspect was also confirmed by the lack of significant difference between the two groups in the attentive matrices and in the trial making test part A, where visual search and processing speed are considered the main underlying mechanisms influencing the performance. Furthermore, cueing effects for both social and non-social cues were observed in both in hearing older adults and in older adults with ARHL, together with similar interference effects of the Flanker task (see for example Erel & Levy, 2016; Gayzur et al., 2014; Gillian Slessor et al., 2016). My prediction of decreased inhibitory control following pure presbycusis was therefore not confirmed, showing that hearing-impaired older adults were not different from hearing older adults in the ability to suppress inappropriate responses to irrelevant stimuli.

Second, my findings point out that older adults with mild to moderate ARHL have reduced validity effects on RTs compared to their hearing peers. The reduced validity effect in ARHL may be interpreted in two different ways. The ability to better ignore the irrelevant central cues may indicate enhanced cognitive control. Alternatively, it may be the sign of a general deficit account, which leads to decreased processing of central information and consequently to reduced validity effects.

Regarding the first hypothesis, a similar finding has been already observed in early profound deafness (Heimler et al. 2015b). Profound deaf adults showed reduced gaze-cueing effect in a spatial cueing task with uninformative social and non-social cues and this effect was ascribed to an enhanced control of visual attention in the presence of social cues, probably deriving from the need to focus on the face area during social interaction and sign language processing. Although my sample of older adults with ARHL seems to exhibit a similar reduction of the validity effect, it may be difficult to argue that this behavior reflects enhanced attentional control and may serve a specific adaptive role. In fact, reduced susceptibility to uninformative cues was not specific to the social cue, but was present also for the non-social cue (see also Bonmassar et al. submitted). Moreover, comparing the results of the present study to previous work with young adults (Bonmassar et al., 2019), my sample of hearing older adults showed a relative increase in the cueing effect. This finding seems to suggest that, in the absence of a disabling sensory loss, aging is associated with an increased reliance on external spatial cues and not vice versa. Nevertheless, neuropsychological assessment additionally revealed a general decline in cognitive and executive functioning in the presence of presbycusis, which does not support the idea of increased cognitive control. As I will describe later, the alternative hypothesis relative to a deficit is more likely to account for this pattern of results in older adults with ARHL.

Third, age-related hearing loss did not appear to specifically impact eye-gaze processing and following, as both groups showed a reduction of gaze-cueing effects especially in the short SOA and on invalid trials. This subtle reduction seems to add evidence in favor of recent hypotheses linking aging with a decline of social perception abilities and decoding of social information from the eye-region. This detriment presumably derives from a deterioration of brain networks in frontal and temporal lobes involved in face and gaze processing (Lin et al., 2014; Slessor et al., 2016; Sullivan & Ruffman, 2004; Ziaei, Ebner, & Burianová, 2017; however, see Smith et al., 2018). Consequently, age-related hearing loss does not seem to further desensitize the processing of social cues and gaze following more than aging per se. Even so, the ARHL observers' perceived disability in emotional and social dimensions as measured by the Hearing Handicap Inventory for the Elderly (HHI-E) was positively associated with the hearing threshold, so that the greater the gravity of presbycusis, the greater the perceived disability in terms of negative emotions and social isolation. Although presbycusis can significantly restrict the individual's participation in everyday activities, family relationships and social interactions, this did not translate into enhanced difficulties in basic face or eye-gaze perception.

Importantly though, the neuropsychological assessment of global cognitive functioning and attention supports the idea that the reduced validity effect in ARHL is due to a general deterioration of cognitive functioning and higher-level aspects of voluntary attention, rather than endorsing the hypothesis of an adaptive reorganization of attentional resources or better control of attention. In the last decades, a number of researchers have already linked age-related hearing loss to cognitive decline (Castiglione et al., 2016; Humes, Busey, Craig, & Kewley-Port, 2013; Lin, Metter, et al., 2011; Loughrey et al., 2018; for reviews see Roberts & Allen, 2016; Schneider & Pichora-Fuller, 2000; Wayne & Johnsrude, 2015) and my data also suggest that the onset of presbycusis at later stages of life negatively affects global functioning. However, the association between presbycusis and other non-linguistic and non-memory related aspects of cognition has been scarcely examined so far. My work adds to literature on hearing loss and cognition by investigating the effects of acquired hearing loss on several aspects of attention, such as selective attention, orienting of attention and divided attention. However, based on the current data, it is difficult to say whether the detriment in aspects of attention following presbycusis is better explained by the sensory-deprivation hypothesis or the common cause hypothesis.

On the one hand, my data may speak in favor of the former, as continuous reallocation of cognitive resources to support speech perception may progressively exhaust the resources available for other cognitive functions. In my case, the difference between the experimental and control group was particularly evident in a highly demanding task like the TMT part B, in which both working memory and attentional resources need to be deployed to solve the task, and in the final measure of shifting ability (TMT B-A), which is considered a good measure of executive functions (Sánchez-Cubillo et al., 2009). In addition, the reduction in validity effect in the cueing task may also indicate that reflexive mechanisms of attentional orienting to nonpredictive central cues are impaired. While one may argue that the reduced validity effect may rather reflect enhanced inhibition of uninformative cues, I think this is unlikely as such enhanced inhibitory control would also be evidenced in the Flanker interference task that similarly taps into inhibition of irrelevant stimuli and in the TMT B-A. However, interference effects in the Flanker task were not reduced and performance in the TMT B-A was significantly worse in participants with presbycusis than that of hearing controls, and these findings seem to speak against an enhancement of inhibitory control.

On the other hand, it cannot be excluded that a mixture of common factors, e.g. cerebrovascular disease and general physical health, may explain presbycusis, vision impairment and detriment in cognitive functioning and attention (see Humes et al., 2013). In my samples, the majority of participants of both groups had corrected vision but with a higher prevalence in older adults with ARHL ($n_{Hearing}$ = 55%; n_{ARHL} = 71%) and almost half of them had pharmacologically treated hypertension ($n_{Hearing}$ = 44%; n_{ARHL} = 45%), while a minority suffered from hypothyroidism ($n_{Hearing}$ = 22%; n_{ARHL} = 10%). Though I acknowledge the fact that self-report cannot be representative of the real cerebrovascular risk and/or disease, the two groups apparently did not differed in terms of cardiovascular risk. The concurrent impairment in vision and a consequent reduction of visual acuity may in part account for the worsening of cognitive functioning in older adults with ARHL, but since I do not have precise information on spared visual acuity, it is difficult to draw firm conclusions. Nevertheless, my participants with impaired vision compensated with and performed all tasks wearing glasses. Additionally, if visual acuity was the factor explaining poor performance in high-demanding cognitive tasks and reduced validity effect in older adults with ARHL, this should be also reflected in the other measures I collected. In fact, attentive matrices and TMT A not only require selective attention, but also intact visuospatial abilities (Sánchez-Cubillo et al., 2009). Furthermore, accuracy in the spatial cueing task using peripheral stimuli was very high in both groups and overall reaction times comparable; I would expect more errors or slower RTs due to poor vision acuity instead of similar performance. Moreover, visual acuity measured by e.g. Snellen charts seems to be poorly informative of the visual impairment in everyday life of older adults, and other more precise and complex measures of vision and global sensory processing may be adopted instead (see for example Humes et al., 2013; Wettstein, Wahl, & Heyl, 2018).

Yet, it remains plausible that concurrent partial blindness and partial deafness can increase the need for additional resources to process stimuli and interact with the environment and with other people, thus permanently reducing the pool of resources at disposal for other cognitive functions. Future research should directly address the potential role played by concurrent vision and hearing compensation, in order to test whether the depletion of additional resources for cognition is an inevitable event or whether targeted interventions may prevent it. In my study, the subgroup of older adults especially with moderate presbycusis reported use of hearing aids (n = 13). Direct comparisons between the group with mild and moderate presbycusis failed to highlight differences in terms of performance on the tasks I proposed. Nevertheless, any interpretation is premature and purely speculative. To better understand the influence of hearing aid rehabilitative treatment on attention and cognition, a cohort of participants matched for presbycusis, i.e. mild vs moderate, with and without hearing aid intervention would be required (see for example Castiglione et al., 2016; Dawes et al., 2015). Moreover, other possible modulatory factors like years of hearing aid use and daily usage may be also taken into account.

Finally, another aspect worth investigating is whether older adults with partial blindness and/or partial deafness may benefit from a combination of sensory compensation (glasses and hearing aids) and cognitive training or multisensory rehabilitation. Several studies have reported improvements in executive functions in older adults without diseases trained on those specific executive functions and also on selective attention (e.g. Kelly et al., 2014; Morrison & Chein, 2011; Reijnders, van Heugten, & van Boxtel, 2013; Rienäcker, Jacobs, Van Heugten, & Van Gerven, 2018). The increase of the cognitive reserve and/or the optimization of the existing cognitive resources are the best candidates to explain potential benefits of cognitive training. If a similar effect arose also in older adults with sensory impairment, this would indicate that cognitive resources can be re-reallocated to improve cognition and attention. Alternatively, multisensory training may foster perceptual integration of vision and hearing in conditions of age-related sensory impairment. Perceptual benefits have been found in older adults without diseases when congruent inputs from different sensory modalities were combined together (e.g. de Dieuleveult, Siemonsma, van Erp, & Brouwer, 2017; Diederich, Colonius, & Schomburg, 2008; Laurienti, Burdette, Maldjian, & Wallace, 2006; Mozolic, Hugenschmidt, Peiffer, & Laurienti, 2012). Yet, little is known about the potential of multisensory training in combination with hearing aid intervention, and researchers have just recently started addressing this question by examining audiovisual integration in hearing aid users and non-users (Gieseler et al., 2018). Lastly, future research can address the question whether a training paradigm based on invoking changes in executive functions would be more or less effective than approaches founded on invoking changes in multisensory cortical networks derived from direct multisensory training methods.

To conclude, the present study examined the effects of age-related hearing loss on the deployment of spatial and non-spatial attention. I suggest that the reduction of cueing effects, the decline in performance in high-demanding attention tasks and in global cognitive functioning in ARHL reflect impairments following acquired deafness rather than adaptive reorganizations. Because cognitive deficits in domains like working memory, executive functions and attentional resources may represent preclinical signs of cognitive decline and dementia, it is of great importance that future research aims at examining whether these impairments can improve by means of sensory intervention and whether older adults with age-related hearing loss can benefit more from cognitive or multisensory trainings.

GENERAL CONCLUSIONS

5.1 Summary of findings

In the present dissertation, I have addressed key aspects of orienting visual attention to socially relevant or non-relevant cues in the presence or absence of deafness and presbycusis. First, I examined how covert and overt attention interact in hearing individuals, as these mechanisms have most often been studied in isolation and the relationship is not clear in the existing literature of central cueing of attention. Second, I used the same approach to inspect how early profound deafness affects the interaction between these two attentional mechanisms, with particular focus on the effect of social and non-social cues on attention. Third, I extended the current literature on the topic of attention in aging, by exploring the consequences of age-related hearing loss on attention orienting.

In the first study, the concurrent registration of oculomotor and manual performance of hearing observers indicated that spontaneous oculomotor behavior, when present, modulated manual responses, in the sense that validity effects were larger and manual responses were overall slower to the non-social cue. Moreover, the findings on saccade latency and landing position corroborated the idea that the when and the where of eye movements have different properties and may be independently associated with the final attentional performance on manual RTs in central cueing of attention. These results extend the current literature on orienting of attention, highlighting the importance of studying covert and overt measures together. While the interplay between these two forms of attention orienting has not been taken into consideration in most computer-based experimental tasks, dissociations between covert and overt attention have been recently documented using real-world social contexts (Laidlaw & Kingstone, 2017; Laidlaw, Rothwell, & Kingstone, 2016; Pereira, Birmingham, & Ristic, 2019), pointing out the importance of combining measures of both mechanisms to better understand social attention.

The first study served as a baseline for further addressing modifications in attention orienting following early profound deafness. The same approach was exploited for the study of oculomotor control in profound deaf adults. By virtue of enhanced peripheral attention resources and of enhanced fixation patterns on the eye region previously reported in this population (e.g. Dye et al., 2007; Emmorey et al., 2009; Heimler, van Zoest, Baruffaldi, Rinaldi, et al., 2015b; Proksch & Bavelier, 2002; Watanabe, Matsuda, Nishioka, & Namatame, 2011), I predicted enhanced fixation in deaf observers, especially in response to the social cue; yet, this hypothesis was not confirmed by the data collected. Deaf observers exhibited a massive recruitment of eye movements during peripheral target discrimination, but, strikingly, this had only a partial effect on manual performance. While deaf observers were overall slower to respond in the manual task compared to the hearing observers, spontaneous eye movements did not affect the validity effect, which was comparable for the two groups and did not vary depending on the cue. Considering the timing and quality of saccades and that spontaneous oculomotor behavior coincided with target and distractor onset, it is unlikely that overt responses were purely automatic reactions. Because the proportion of cue-elicited eye movements and validity effects of deaf and hearing observers were alike, it may be the case that the actual shift of attention and incurred costs occurred before the triggering of the saccades. Therefore, the increased number of eye movements by the deaf observers might reflect increased responsiveness to the target. In other words, the enhanced need to align the fovea in the direction of the target may reflect a modification in oculomotor control following deafness only. Their oculomotor system may be more sensitive to stimuli suddenly appearing in peripheral regions of the visual field, similar to covert attention (Bavelier et al., 2000; Bavelier et al., 2006; Bottari et al., 2012; Proksch & Bavelier, 2002). Yet, this reactiveness is subject to top-down control, as shown by the relatively high latencies of the saccades. The overt response would act as an additional check towards the valid target position once the validity of the cue is unveiled. The adaptation of visual abilities to task demands and the prioritization of attentional control over reflexive orienting may come at expenses of speed in later stages of response selection.

Finally, I started examining whether a form of partial deafness, i.e. acquired and associated with aging, leads to similar changes in attention orienting. To my knowledge, there has been very little work done to investigate attention orienting in older adults with presbycusis. Hence, I started a first exploration of diverse aspects of attention, including covert orienting, inhibitory control and divided attention. My results showed that older adults with pure presbycusis exhibited comparable processing speed and inhibitory capacity, even though they presented a significant reduction of validity effects on spatial cueing of attention, irrespective of cue type. A similar reduction was reported in deaf adults but only in response to social cues (Heimler, van Zoest, Baruffaldi, Rinaldi, et al., 2015b); this finding has been interpreted, in the context of early profound deafness, as a sign of enhanced attentional control to promote visual processing and extraction of information from a social cue during e.g. sign language comprehension. However, in the sample of older adults, worse performance on the Montreal Cognitive Assessment (MoCA) and on tasks requiring divided attention and flexibility seems to indicate that the broader attention network is less efficient in this population. Under this view, the reduction of the validity effect may rather point towards a deficit in paying attention to central cues or processing these stimuli. Having found that pure presbycusis has a large impact on central cueing, it would be very interesting to investigate performance in response to peripheral cues in this population. Moreover, there are many other factors that can be taken into consideration and lead to important insights, e.g. the potential benefit of hearing aid intervention on cognition, individual differences in working memory capacity or the use of more realistic tasks to investigate attention mechanisms.

5.2 Implications

From the findings I have presented so far, what can we infer about mechanisms of plasticity following deafness at different life stages?

At the beginning of my dissertation, I have presented the *deficit* and the *compensation* hypothesis as the two main frameworks that characterize research on cognition in the long-term sensory deprived brain. The debate arisen from the two opposed views have stimulated and encouraged researchers to test these hypotheses through a variety of tasks, spanning from psycholinguistics to face processing to visual attention and touch. This has undoubtedly contributed to the further understanding of deaf cognition and of the dynamics of brain plasticity. Behavioral adaptations, e.g. in vision and visual attention, are considered to effectively compensate for the lack of auditory input when exploring and monitoring the environment; yet, as already mentioned, growing evidence suggests that they slowly and progressively develop from childhood to adulthood, therefore being influenced also by brain maturation and by external factors, e.g. sign language learning, social interactions, etc.

Two key aspects emerge from the investigation of plasticity mechanisms in deafness: 1) The context appears to play a very important role in modulating the observed behavior, indicating that a mechanism can be adjusted on the basis of the task, or of individual or environmental constraints; 2) Changes at a behavioral and at a neural level after early deafness could be recognized as an adaptive behavior to the specific constraints caused by deafness, rather than perceived as purely deficient or compensatory strategies. For example, the fact that profound deaf adults in Study 2 do not show increased fixation to the face during the cueing task could be explained by the lack of linguistic properties of the gaze cue. Previous research has pointed out how deaf observers tend to fixate more the eye-region and the face during sign language comprehension (e.g. Emmorey, Thompson, & Colvin, 2009). The fact that my cue did not carry such linguistic information may be the reason why deaf adults did not maintain fixation more on the face in the presence of peripheral stimuli. Despite being intriguing and in line with the idea of a flexible management of visual attentional resources depending of the context, further research that directly manipulate linguistic information of social cues is needed to test the validity of this interpretation.

Another critical point to raise in the study of automatic orienting mechanisms of attention is the fact that central cues are nonpredictive, i.e. uninformative, of target location; however, this is rarely experienced or encountered in everyday contexts and could change the value attributed to the cue itself. Hence, a social cue embedded in a different context may elicit other behavioral responses in this population of deaf observers. On the one hand, the presence and heavy reliance on eye movements during an easy target discrimination could be interpreted as a sign of disinhibition and lack of control of the oculomotor system following deafness. On the other hand the slowing down of manual responses in the presence of high accuracy rate and comparable validity effects may rather reflect and increased sensitivity to the task demands and increased control as a result of visual adaptations to deafness.

In the case of late-life acquired partial deafness, the potential link between presbycusis and cognitive decline has fostered research aiming at determining the direction of this relationship, as well as the presence of other factors influencing both presbycusis and cognitive decline. In Study 3, findings on attentional abilities seem to indicate that late-life adaptations in vision and visual attention may be ineffective in coping with the acquired deafness. Successful plastic modifications in the brain and in behavior following presbycusis may be subject to age constrains and limited by concurrent natural aging processes, which are characterized by neurocognitive changes and structural alterations of the brain. Yet, firm conclusions on the effects of late-life sensory plasticity on cognition cannot be drawn by only looking at this set of data and considering the general lack of similar studies in the current literature. Nevertheless, the topic of plasticity following acquired deafness in aging raises several still unanswered questions: 1) Are visual adaptations taking place as a function of the onset of presbycusis? As mentioned above, plasticity after early deafness appears to follow a developmental trajectory and, similarly, these reorganizations may be present late in life but occurring too slowly to be effective in compensating for the impaired sense in the aging population; 2) Can older adults with age-related hearing loss benefit from hearing aid interventions and concurrent cognitive and multisensory trainings? These external factors may promote and elicit forms of experience-dependent plasticity, which e.g. is also thought to mediate changes in attentional control in deaf individuals during development. In addition, converging evidence supports the notion that cognitive and multisensory trainings optimize or ameliorate cognitive functions and cognitive resources, which may in turn be helpful in diminishing hearing-related deficits; 3) Are there any contexts and situations, in which vision and visual attention "replace" or aid impaired hearing? In my work, I have been unable to examine peripheral attention or oculomotor control in older adults suffering from presbycusis. These aspects of attention remains unexplored and will deserve further research in the future. Attention is a fundamental cognitive process capable of influencing other aspects of cognition, but because attention is very complex and multifaceted, more studies examining the effect of age-related hearing loss on a variety of attentional tasks are needed.

As a concluding remark, it is important to note that deafness and age-related hearing loss are two types of lack of auditory input that are doubtless very different in their etiology and in the moment in life they occur. Hence, to achieve a more comprehensive understanding of sensory plasticity as a function of age and etiology, other cohorts should be considered in the future, e.g. younger adults with acquired mild to moderate deafness (see Glick & Sharma, 2016 for a first review on the topic of crossmodal plasticity across the lifespan that considers different forms of deafness). At present, my results are compatible with the hypothesis that developmental hearing loss (early profound deafness) is able to modify both covert attentional orienting, oculomotor control and their interplay. The fact that in the literature both increased and reduced attentional and oculomotor control have been documented may depend on tasks demands and task constraints. Instead of interpreting changes in deaf individuals purely as a sign of either compensation or deficit, another perspective can be adopted: these alterations may reflect a collection of attentional and oculomotor signatures related to the demands imposed by early deafness. Conversely, my present data on the aging population suffering from presbycusis suggest that possible plasticity effects spontaneously developing later in life may not be effective. Concurrent age-related physiological processes and the implications of impaired hearing for cortical structures beyond the auditory cortex (see Lin et al., 2014) may severely limit the reorganization of vision and visual attention. However, this does not entirely exclude the possibility that other forms of brain and functional plasticity may develop after appropriate hearing and cognitive interventions, considering other physical, psychological, and cultural factors as potential mediators of changes in the brain and behavior (Mora, 2013).

As this fascinating field of research is still in its infancy, more studies are required to better characterize the strengths, limitations and the mechanisms underlying cross-modal brain plasticity in younger and older populations with deafness, as these may substantially differ in developmental versus adult- and late-onset forms of deafness.

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