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Attentional enhancements and deficits in deaf populations: An integrative review

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Abstract. The literature on visual attention in deaf individuals presents two competing views. On one hand, the deficit view proposes that auditory input is necessary for the development of visual attention; on the other hand, the compensation view holds that visual attention reorganizes to allow the individual to compensate for the lack of auditory input. While apparently contradictory, we suggest that these views shed complementary light on the cross-modal reorganization of visual attention after early deafness. First, these two fields of inquiry look at different aspects of attention. The deficit view is mostly supported by studies of allocation of attention in time, whereas the compensation view is backed by studies measuring the allocation of attention across space. Second, they focus on groups of different age and different background. Deficits have been documented mostly in children with mixed hearing loss aetiologies, whereas reorganization has been documented in a less representative, but more homogenous group of Deaf adults. We propose a more integrative view in which early auditory deprivation does not result in better or worse visual attention. Rather, selected aspects of visual attention are modified in various ways along the developmental trajectory as a result of early deafness.

Keywords: deafness, RSVP, spatial attention, attentional blink, temporal segmentation, cross modal plasticity

1. Introduction

Over the past twenty years, there has been a renewed interest in the possibility that early sensory deprivation may lead to enhanced perceptual and cognitive development in the remaining modalities (see Bavelier and Neville, 2002; Pascual-Leone et al., 2005; Sadato, 2005 for reviews). However, in the case of early auditory deprivation there has been some debate over whether early profound deafness results in visual attention deficits (Quittner et al., 2007) or compensatory changes to attentional processes (Neville and Lawson, 1987a; Bavelier et al., 2006). In this brief article we attempt to reconcile these two views by contrasting attentional selection in space versus in time. The former refers to looking for a target within a visual scene and having to select the target on the basis of its spatial location. The latter refers to looking for a target embedded in a stream of objects presented one after the other and having to select the target based on its time of appearance. We present data which suggests that there may be some early deficits in visual attention in time in profoundly deaf individuals, but that these deficits are overcome by adulthood. In contrast, attention in space appears to be enhanced, at least in deaf individuals who have full access to a natural language and social environment from birth.

1.1. The deficit view

The *division of labor hypothesis* (Quittner et al., 2007) holds that integrative processes, such as multisensory integration, are essential for normal development. Thus, in the absence of auditory input, there is a loss of redundancy and a consequent impairment in the development of normal visual processing.

Using a continuous performance test to assess the visual attention skills of young deaf children, Quittner

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and colleagues (Horn et al., 2005; Quittner et al., 1994; Smith et al., 1998) have suggested that early auditory deprivation results in visual selection deficits that can be ameliorated to some extent by cochlear implantation and the restoration of audition. In the visual selection form of the continuous performance test, the child views a stream of rapidly presented digits. Her task is to press a key whenever she sees a '9' that was immediately preceded by a '1'. Thus the task requires the child to be vigilant and to make selective responses to the number '9' (which may or may not be preceded by a '1').

Quittner et al. (1994) compared the performance of three groups of 6–13 year old children on this task: children with no hearing loss, deaf children who used hearing aids, and deaf children who had received a cochlear implant (CI). For the youngest children (6–8 years old) they reported that both groups of deaf children had lower perceptual sensitivity on the task than their age-matched hearing controls. In addition, the 6–8 year old deaf children who had undergone cochlear implantation had greater perceptual sensitivity then those deaf children who used hearing aids and had not received a CI. In older children (9–13 years old) they reported that those deaf children who had received a CI achieved a similar level of performance to their age-matched hearing controls, unlike deaf children who used hearing aids and had not been implanted. Quittner and colleagues followed up their findings with a longitudinal study, demonstrating that this effect appeared due to the length of time since cochlear implantation.

Smith et al. (1998) used the same continuous performance test with a larger sample of children and a more fine-grained banding of ages. Their results suggested that while all three groups of children start to improve on the task around the age of 8 years, the magnitude of the age-related improvement in performance was larger for hearing children and deaf children who had received a CI than it was for deaf children who had not been implanted (a finding also supported by Horn et al., 2005 – but see Shin et al., 2007 for a different outcome). In a subsequent task that required an absolute response to the digit '0' not conditioned by any previous digit, Smith et al. (1998) reported marginally greater sensitivities for CI children than for un-implanted deaf children, although both groups performed at levels considered abnormal based upon hearing norms. The differences between implanted and un-implanted deaf children were, however, much lower than observed using the visual selection version of the continuous performance test. Based upon these data, both Quittner et al. (1994) and Smith et al. (1998) conclude that cochlear implantation leads to enhanced access to sound (either speech or environmental), and that the auditory input helps to organize visual attention, supporting a deficit view of cross-modal reorganization as a result of early sensory deprivation.

1.2. The enhancement view

In contrast to the deficit view, several research groups have reported a reorganization of visual attention following early auditory deprivation that results in some degree of compensation. The argument being put forward here is that the visual system reorganizes to compensate for the lack of auditory input, such that visual skills now take over the functional role performed by audition in the typically developing child. In support of this view, many studies suggest that there is a spatial redistribution of visual attention toward the periphery, allowing deaf individuals to better monitor their peripheral environment based upon visual rather than auditory cues. A selective enhancement in deaf adults for stimuli that are peripheral has now been demonstrated using a variety of behavioral paradigms. Loke and Song (1991) showed that deaf participants reacted to a peripheral stimulus with an abrupt onset more rapidly than did hearing participants. Using kinetic perimetry, Stevens and Neville (2006) reported that deaf adults were better at detecting a moving light in the periphery but showed no such enhancement in a static perimetry task presented at fixation.

Neural correlates of this attentional enhancement have been documented using event-related potentials and functional magnetic resonance imaging, often by requiring participants to attend to motion in the visual periphery (Bavelier et al., 2000, 2001; Neville and Lawson, 1987a,b). These studies provide converging evidence for the proposal that multi-sensory associative cortical areas reorganize in the face of missing auditory input by displaying a greater sensitivity to the remaining modalities, such as vision. Accordingly, differences between deaf and hearing adults have been reported in the posterior parietal cortex and the superior temporal gyrus when attention has to be directed peripherally. Each of these areas is a zone of multisensory convergence as well as a main player in the control of attentional allocation (Bavelier et al., 2000, 2001; Finney et al., 2001). This finding is reminiscent of that documented in the animal literature on cross-modal plasticity, and is well accounted for by a competitive, Hebbian-like mechanism whereby in the absence of competition from auditory inputs, the remaining modalities exert a greater influence over multi-modal cortices.

A direct behavioral consequence of greater peripheral attention in the deaf is greater processing of peripheral information. As a result, irrelevant peripheral information will be more distracting to deaf than to hearing individuals. For example, greater task interference from peripheral distractors for deaf than for hearing subjects has been reported in a number of studies (Dye et al., 2007; Proksch and Bavelier, 2002; Sladen et al. 2005). Crucially, the opposite pattern is observed in the few studies that have manipulated central distractors (Proksch and Bavelier, 2002). Hearing individuals are more distracted by irrelevant central information, whereas deaf individuals are more distracted by irrelevant peripheral information. This work shows that deaf and hearing individuals differ in where they allocate their attention over the visual field, rather than in their overall level of distractibility.

Attention is far from being a unified construct; rather, attention varies depending on the content that needs to be selected (space, time, visual features such as color, or objects) and the way attention is initially engaged (exogenous versus endogenous). When considering these varieties of attention, deaf and hearing adults have been found to be quite comparable. Using the multiple object tracking task, Hauser et al. (2007) have shown that deaf adults and hearing adults can track the same number of objects, indicating equivalent allocation of attention to dynamic visual objects. Exogenous attention also seems unaffected by early deafness. Using the Attentional Network Test (ANT) with deaf and hearing adults, Dye et al. (2007) reported no effect of deafness on measures of alerting and orienting, which respectively index the ability to harness and direct attention spatially following the presentation of an exogenous cue. In the case of alerting, the exogenous cue informs the subject to get ready, but does not provide precise location information. In the case of orienting, the exogenous cue is spatially informative and provides disambiguating information among the expected spatial locations of the target. Both groups benefited equally from such cues (see, however, Bosworth and Dobkins (2002) for the suggestion that deaf individuals obtain greater benefits from valid spatial cues, and also Parasnis and Samar (1985) for the suggestion that deaf individuals may have an enhanced ability to disengage attention after it has been misdirected by an invalid spatial cue). Although a recent report by Bottari et al. (2008) using a change blindness task argues that early deafness may change exogenous but not endogenous attention, we note that the results on which this conclusion was based did not hold when only deaf adults were considered. We argue here that differences in attention between deaf and hearing adults are largest when attention has to be endogenously engaged (see Röder et al. (1996) for a similar argument with respect to cross-modal plasticity in blind individuals). A review of the literature on spatial attention indicates that deaf individuals outperform hearing individuals mostly under conditions of maximal uncertainty when the location and/or the exact time of the onset of the target stimulus is unknown (see Bavelier et al., 2006 for a review). It remains possible that exogenous and endogenous attention exhibit different susceptibility to early deafness along the developmental time course. Further studies in this area should be quite informative.

A common finding across the studies that have found differences in attention between deaf and hearing is that events in the visual periphery are processed more efficiently in deaf individuals than in hearing controls, especially when there is competition for resource allocation between the center and peripheral visual fields (see Bavelier et al., 2006 for more discussion). It is important to note that these studies have typically been conducted with deaf adults who are native or near-native users of American Sign Language (ASL), raising the issue of the relative contribution of deafness and sign language acquisition. Several studies have controlled for the possible impact of a visuo-spatial language by including hearing individuals who acquired American Sign Language from infancy as their native language. These studies establish that it is early auditory loss that plays the key role in the cortical reorganization of attention to the periphery, and not the early acquisition and use of a sign language (Bavelier et al. 2001; Dye et al., 2009; Neville and Lawson, 1987c; Proksch and Bavelier, 2002).

1.3. Reconciling deficit and enhancement approaches

The studies reviewed so far make it clear that it is still an open question as to whether early auditory deprivation results in visual attention deficits or a compensatory reorganization. Yet, the extent to which these findings reflect a true discrepancy in the field is questionable. We note that in the visual selection form of the continuous performance test as employed by Quittner and colleagues, temporal selection appears to be crucial. In order to succeed on the task, the subject must be able to temporally segment the stream of digits into a temporally-ordered set of discrete stimuli, attend over time to those stimuli such that an accurate perceptual decision can be made about the identity of each digit in the stream, and also switch their attention from one digit to a subsequent digit such that a decision can be made as to whether a target sequence has occurred and an appropriate response made. Thus, rather than being a simple measure of selective visual attention, the continuous performance test is complex and requires a set of potentially independent attentional skills. One way in which the continuous performance test differs from the tasks employed by other groups of researchers is in its strong temporal component – target selection has to be made based on the relative time of occurrence of the items. It is under these attentional conditions that deaf children are found to be at risk. In addition, the deaf children studied have varied widely in their aetiology, with deafness often being only one component of a larger compromise of the central nervous system (Horn et al., 2005; Quittner et al., 1994; Smith et al., 1998). Even if free of co-morbidity, these deaf children, mostly born to hearing parents, likely experience abnormal social communication as a result of their limited access to a natural language (Peterson and Siegal, 2002). The effect of such social and language deprivation on attentional skills remains largely unknown. In contrast, studies of spatial attention indicate that deaf individuals raised with a natural language from birth exhibit normal or enhanced spatial attention skills at least by the time they have reached adulthood.

Reconciling the deficit and the compensation approaches will require a push on several research fronts. First, it is important to look at similar aspects of attention. Attention is a multi-component process and the neural systems that support the control and allocation of attention vary depending on the type of attention considered. Compared to spatial selection, little is known about attentional selection in time. This is certainly a gap that needs to be filled. Second, it is crucial to compare across studies using comparable age groups. Very few studies have investigated spatial attention in deaf children, whereas the bulk of the attention in time studies have focused on deaf children. There is one comprehensive study of spatial attention in deaf children and adults (aged 6 to 20 years) using a visual search paradigm (Rettenbach et al., 1999). This study documents similar performance between deaf and hearing children on displays where the search target is present. A difference was noted on target-absent trials with deaf children terminating their search earlier than hearing controls. This latter finding suggests different strategic biases rather than differences in attention. This study makes it clear that deaf children are not systematically at risk for attentional problems. Third, it is important to examine how attentional skills vary as a function of deafness aetiology and other related variables. We note that most of the studies of deaf children that have documented attentional deficits have recruited children born to hearing parents, with mixed aetiologies and little-or-no access to language during the first years of development. On the other hand, those studies that have documented attentional enhancements have focused upon Deaf adults with sensori-neural hearing losses of predominantly genetic origin who are also native signers of American Sign Language. In conclusion, progress in reconciling deficit and compensation views is likely only by carefully assessing individual components of attentional skill in samples of deaf and hearing individuals at different developmental stages, and by controlling for demographic variables known to vary widely in deaf populations such as language experience and aetiology of hearing loss.

This is the approach we have adopted in our studies of visual attention development in deaf individuals. In a recent paper (Dye et al., 2009) we have reported on a cross-sectional study looking at the development of attention over space in congenitally deaf and hearing children and adults who use American Sign Language as a first or native language. Using the Useful Field of View paradigm (Ball and Owsley, 1993) to assess the spatial distribution of visual attention resources in Deaf adults we observed an enhanced ability to detect a peripheral target embedded in a field of distractors while simultaneously discriminating the identity of a concurrent central target. Interestingly, while Deaf adults outperformed hearing adults on this task, 7–10 year old Deaf children performed similarly to their hearing age-matched peers. Thus, we observed a compensatory redistribution of visual attention resources to the peripheral visual field as a result of early auditory deprivation, but this compensation is slow to develop and not observable in elementary school children. In the study reported here, we examined temporal aspects of visual attention in a similar, albeit smaller, sample of young deaf children and deaf adults.

2. Temporal aspects of attention: Selection and recovery

In a preliminary study of temporal components of attention in deaf populations, reported here for the first time, we tested deaf and hearing individuals (aged 7–10 and 18–40 years) on two dynamic measures of visual attention – the rapid serial visual presentation (RSVP) task and the attentional blink (AB) task. In the RSVP task, a subject is presented with a series of objects, appearing one at a time in the same location. Their task is to monitor the stream of objects and identify pre-specified targets within the stream. The RSVP task thus provides a measure of temporal visual selection. The attentional blink (AB) is an effect that occurs when a subject must respond to multiple objects in a rapid serial visual stream (Raymond et al., 1992; Raymond, 2003). The closer two target objects are temporally within the stream, the harder it is to successfully make a decision about the second target after processing the first. It is not that the second target has not been seen, just that there are insufficient attentional resources available to be allocated to the second item in order to facilitate a perceptual decision. By manipulating the time between the appearance of the first and second target items (termed the T1–T2 lag), the AB task provides a measure of the speed with which attentional resources recover over time after having been allocated to a first target. It is known that this aspect of attention in time can be altered by experience. For example action video game players display faster AB recovery than their non-gamer peers (Green and Bavelier, 2003). Both the RSVP and AB protocols and stimuli were taken from a study of attentional development in children reported by Garrad-Cole and Shapiro (2003) and therefore known to be sensitive to age-related changes. We will contrast these results with tests of attentional selection in space collected from the same sample of individuals using a subset of the data reported by Dye et al. (2009).

In order to assess the effects of auditory deprivation in the absence of significant language delay or co-morbid disorder, deaf participants were selected to (a) have a severe-to-profound hearing loss $>$ 70dB SPL in the better ear that was not the result of neurological insult due to maternal rubella, bacterial meningitis or head trauma, (b) be native or near-native users of ASL (either acquired from birth from deaf parents or in the first few years of life in pre-K education), (c) have no diagnosed attentional deficit or learning disorder, (d) have not received a cochlear implant, and (e) in the case of elementary school children, have no educational accommodations not attributed to deafness.

Elementary school children were aged between 7 and 10 years at the time of testing with mean ages of 8 years 10 months for hearing children ($n = 42$, 16 males) and 9 years 8 months for deaf children ($n = 8$, 5 males). Hearing children were recruited from a local school district (Brighton Central School District, Rochester, NY) and deaf children from a residential/day school in Texas (Texas School for the Deaf, Austin, TX). Informed consent was obtained from all children and a parent or legal guardian, and children were rewarded with a $15 gift card for their participation. Adult participants were aged between 18 and 40 years at the time of testing with mean ages of 20 years 6 months for hearing adults ($n = 33$, 3 males) and 29 years 9 months for deaf adults ($n = 14$, 5 males). Hearing adults were recruited from a participant pool at the University of Rochester (Rochester, NY) and were paid $8/hour for their participation. Deaf adults were recruited from staff at a deaf school in Texas (Texas School for the Deaf, Austin, TX), as well as from participant pools at the National Technical Institute for the Deaf (Rochester, NY) and Gallaudet University (Washington, DC).

Out of the 8 deaf children and 14 deaf adults tested, 3 children and 4 adults had hearing parents, although all reported learning ASL from an early age. Parental hearing status had no discernable effect on the measures used, and thus the data from all deaf individuals were collapsed in the analyses. During a pre-test interview, all children and adults were asked about their videogame playing habits. Those who reported playing action-based videogames were classified as 'game players'. Data from game players are not considered here, and those individuals are not included in the sample data above, as data from Green and Bavelier (2003) suggests that playing action-based games may result in significant alterations to visual attention skills.

2.1. Temporal visual selection – The RSVP task

The RSVP procedure was administered before and after the main AB task. Each participant was presented with a series of colored line drawings of simple geometrical shapes one at a time in the center of the screen (Fig. 1). Each shape was presented for 40 milliseconds, with a 66 millisecond blank interval between each shape presentation. In this procedure there was a single target shape. For half of the subjects the target was a red isosceles triangle either pointing left or right; for the other half of the subjects the target was a blue isosceles triangle either pointing up or down. Participants were asked, at the end of each sequence, to indicate which of the two isosceles triangles they had seen. There were 16 trials in each block, for a total of 32 RSVP trials. This task provided both a baseline measure of how well any one individual could be expected

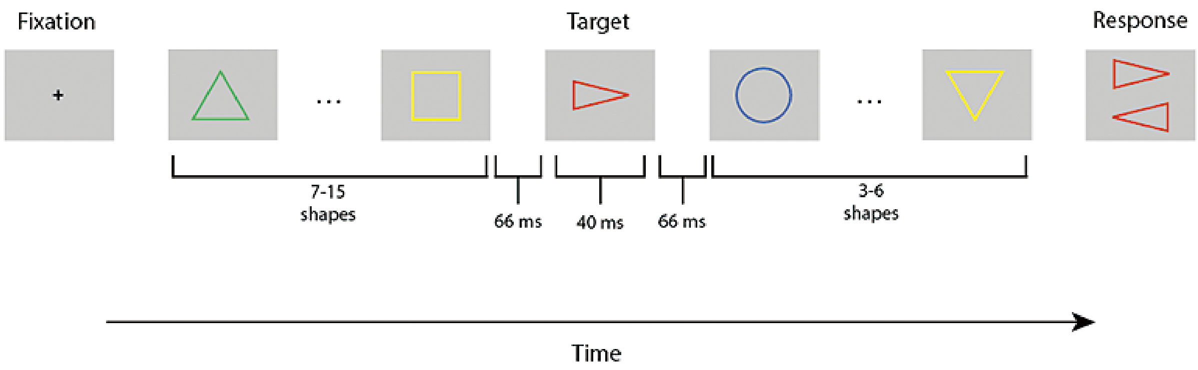

Fig. 1. In the RSVP task, participants saw a stream of colored line drawings of geometric shapes appear one after the other in a central location. Their task was to identify a target shape, which for some subjects was a red isosceles triangle pointing either left or right (illustrated here), and for others a blue isosceles triangle pointing either up or down. Responses were made via a touch screen once the presentation of a whole stream of shapes had finished.

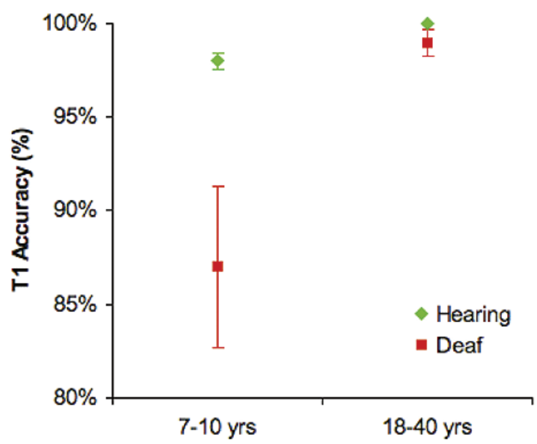

Fig. 2. Data from the RSVP (single target) task indicate poorer performance by deaf 7–10 year olds, resulting in a significant interaction between age group and deafness. Error bars represent the SEM.

to perform in the absence of an attentional blink (see below), and a measure of how well participants could select a single target shape from a temporal sequence of shapes.

Analysis of target identification accuracy in the RSVP task revealed an apparent deficit for young deaf children (Fig. 2). Identification accuracies for each subject were entered into a two-way ANOVA with age group (7–10 years, 18–40 years) and deafness (deaf, hearing) as between subjects factors. This revealed a significant interaction between age group and deafness: $F(1, 93) = 24.55, p < 0.001$.

2.2. Temporal visual recovery – The AB task

Another paradigm adapted from Shapiro and Garrad-Cole (2003) was used to assess the rate of recovery following an attentional blink. This AB task employed similar stimuli and a similar procedure to the RSVP task, except that embedded within the stream of shapes were two isosceles triangles that functioned as targets (T1 and T2). One was red and pointed either left or right; the other was blue and pointed either up or down (Fig. 3). At the end of the stream, participants were required to indicate the identity of T1 and then of T2 using a touch screen (as in the RSVP task). The presentation of these stimuli as T1 or T2 was counterbalanced across participants but held constant for any one individual, with T2 matching the target used in that individual's RSVP task. Between one and seven shapes could appear before T1, and from three to six shapes could appear following T2, determined randomly on a trial-by-trial basis. The number of shapes between T1 and T2 was manipulated systematically: the T1-T2 lag was either 1, 2, 4, 6, 8, 10 or 12 shapes, with each lag occurring an equal number of times.

The attentional blink task indexes the dynamics of attentional recovery, by measuring performance on T2 given that T1 has successfully attended. Figure 4 illustrates the Attentional Blink performance for all 4 groups by plotting T2 performance on all the trials in which T1 was correctly identified, as a function of the T1-T2 lag. First, at the longest lags (8–12 items), performance is seen to be stable in all 4 subject groups (Fig. 4, Panel A). The only observed difference was that adults outperformed children, with no effect of lag nor deafness. This suggests that all participants had recovered by the end of this interval, with asymptotic recovery being higher for adults than for children. Second, at the intermediate lags (2–6 items), performance is seen to improve as the lag increases (Fig. 4, Panel B). The only observed difference is that recovery is faster

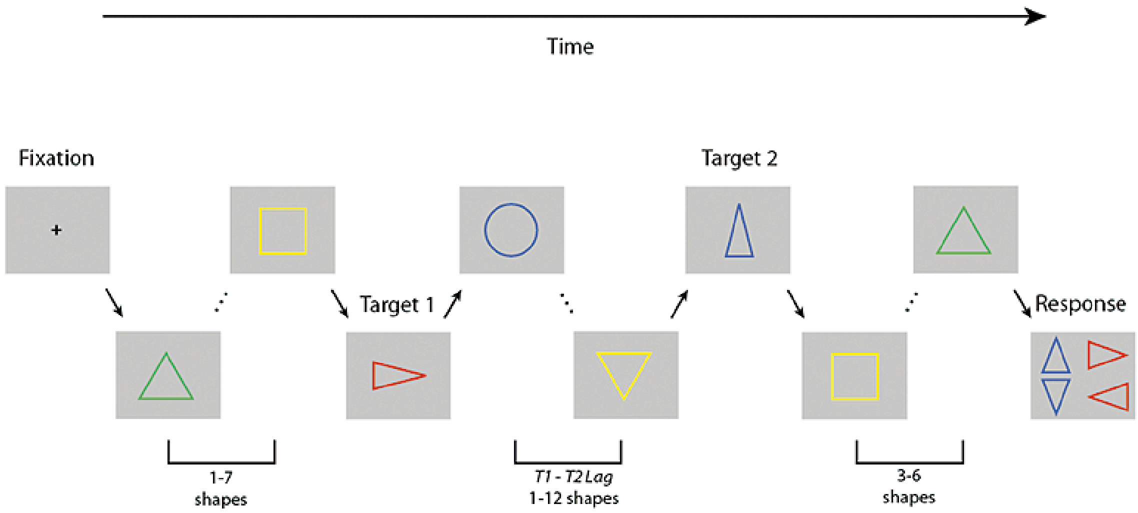

Fig. 3. The AB task was similar to the RSVP task, but the participant was required to identify two targets: is the red isosceles triangle pointing left or right (T1); is the blue isosceles triangle pointing up or down (T2). Typically, when T2 follows soon after T1, it is difficult for an observer to correctly identify T2 – the 'attentional blink'. The proximity of T1 and T2 (T1-T2 lag) was systematically varied in order to determine the time required for a participant's attention to recover and then promote identification of T2.

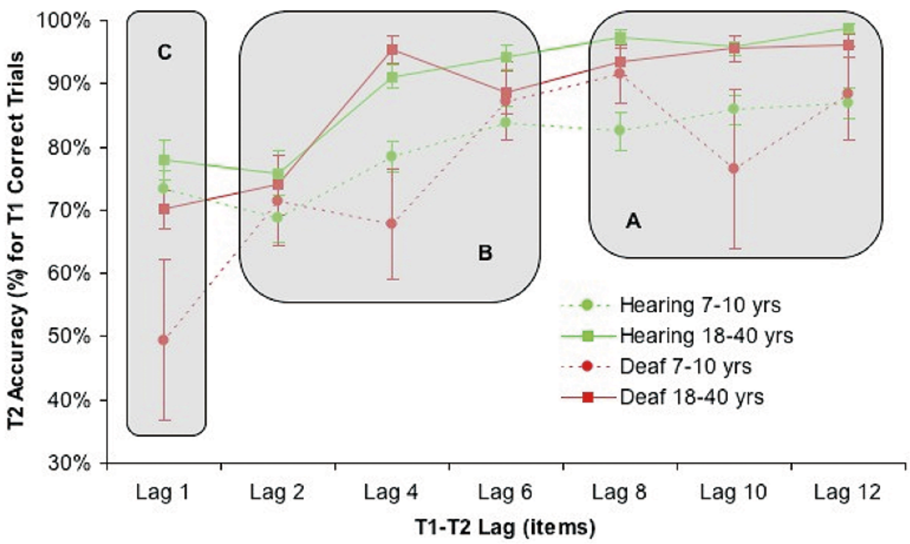

Fig. 4. A. At the longer lags (8 through 12 items) there was a main effect of age group ($F(1, 93) = 27.58$, $p < 0.001$) but no other significant effects. Attentional recovery therefore appears complete after ∼800 ms in both populations, with older participants recovering to a higher level of accuracy than younger participants. Subsequent analyses discounted trials at these lags, focusing upon lags where attentional recovery is in progress. B. Between lags 2 and 6 there are clear age-related differences in attentional recovery, characterized by a T1-T2 lag by age group interaction: $F(2, 186) = 5.18$, $p < 0.01$. Recovery from the attentional blink is faster for adults than for 7–10 year olds, confirming the findings of Shapiro and Garrad-Cole (2003). **C.** Inclusion of the data from lag 1 reveals a three-way T1-T2 lag by age group by deafness interaction: $F(3, 279) = 32.65$, $p < 0.05$. Thus, while the rate of attentional recovery seems comparable for deaf and hearing participants, deaf children aged 7–10 years are significantly poorer at correctly identifying T2 when it appears immediately after T1.

in adults than in children. At a T1-T2 lag of 4 items (∼400 ms), adult performance was around 95% for T2 given T1 was correctly recalled, whereas the identification accuracy of children was only around 70–75%. This corroborates the findings of Shapiro and Garrad-Cole (2003) and suggests that temporal components of visual attention are continuing to develop throughout the school-aged years. Importantly no effect of deafness was noted. The performance of deaf and hearing individuals on the attentional blink task was therefore

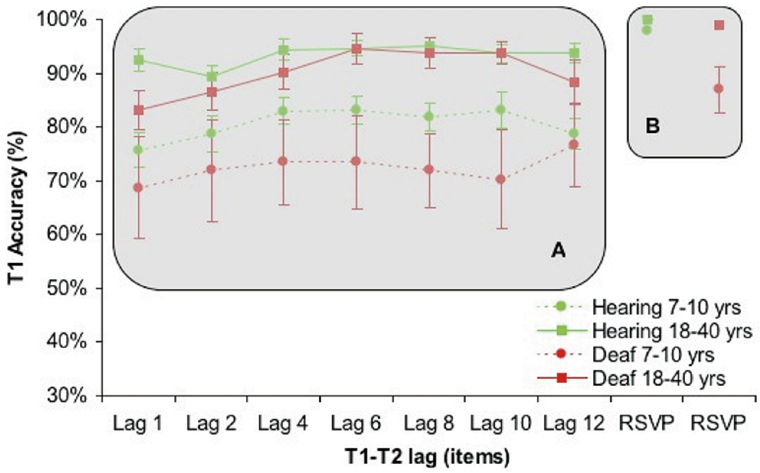

Fig. 5. A. T1 identification accuracy in the AB task was worse for children than for adults ($F(1, 93) = 24.96, p < 0.001$), with a trend for even poorer performance in deaf children. Overall, for all participants, T1 performance was worse in the AB task than in the RSVP task. This may reflect the phenomenon of 'attentional waking' (Ariga and Yokosawa, 2008) where increasing the number of distractors prior to a target improves performance. B. Data from the RSVP task (replotted from Fig. 2).

remarkably similar. Deaf and hearing, whether children or adults, showed similar rates of recovery of attention (Fig. 4, Panels A and B). This suggests that the temporal dynamic of attentional recovery may not be susceptible to alteration – positive or negative – by early profound auditory deprivation. This is in line with several other studies reporting no differences in temporal components of visual attention in deaf individuals (Bross and Sauerwein, 1980; Nava et al., 2008; Poizner and Tallal, 1987).

A marked difference between deaf and hearing children was noted, however, at a T1-T2 lag of one item (∼100 ms). Having identified T1 correctly, it was disproportionally more difficult for deaf children to correctly identify T2 (Fig. 4, Panel C). To better understand this effect, we turn to the analysis of T1 performance.

Identification of T1 in the AB task is plotted in Fig. 5 (Panel A). The data points represent T1 (first target) identification accuracy, and thus correspond to temporal selection rather than temporal recovery. The analogue measurement from the RSVP task, in which a single target was presented, is reported again in Fig. 5 (Panel B). In both the RSVP and AB tasks, deaf children showed compromised performance with identification accuracy for T1 about 10%-20% below their hearing peers. Deaf adults showed the same trend as deaf children but only at a short T1-T2 lag in the attentional blink task and not in the RSVP task. In line with the deficit proposal, this pattern of data indicates attentional difficulties in deaf children, and to a certain extent deaf adults, when monitoring a sequence of items and having to select one item from a stream of events. This pattern of results combined with poorer performance at lag 1 in the AB task suggests it may take longer to initially engage attention in time in deaf participants. Yet, even in the face of this difficulty, deaf participants subsequently show equal rates of recovery function following the attentional blink, indicating that not all aspects of attention in time are compromised by deafness.

3. Temporal versus spatial attention in deaf populations

3.1. A temporal attention deficit in deaf children?

It is important to note that the data reported above are not intended to confirm a hypothesis. Rather they come from an exploratory study and thus are intended to lead toward the generation of a testable hypothesis. In that respect, together with the work of Quittner and colleagues (Horn et al., 2005; Quittner et al., 1994; Quittner et al., 2007; Smith et al., 1998), this study points to a potential attentional deficit in deaf children when having to select a target from a temporal sequence. Deaf children have difficulties identifying a pre-specified target from a rapid stream of visual information presented at fixation. Importantly, not all aspects of attention in time are at risk in deaf children. The same deaf children display similar recovery time from the AB as their hearing peers. The dynamics with which attention recovers once it has been engaged on a target of interest is therefore equivalent across groups.

In accord with what has been proposed by Quittner et al. (2007), this pattern of results is well captured by the proposal that deaf children have difficulties in the initial engagement of their attention upon a stream of stimuli presented in the center of their visual field. As a result, they are particularly poor at identifying the first target in an RSVP stream whether it is in the context of a single target in an RSVP task or T1 identification in the AB task. If T1 is correctly identified however, they show no deficits on T2 identification.

This overall pattern of data may also result from having to select overlapping items in the center of the screen. While there are several accounts of lag 1 sparing in the literature (Chun and Potter, 1995; Olivers and Nieuwenhuis, 2006; Visser et al., 2009), they all share the proposal that this effect reflects an overcommittment of attentional resources to T1. As a result, T2 is often processed concurrently with T1 when it appears soon afterwards. If deaf children were to have fewer attentional resources to commit to T1, this would predict less lag 1 sparing as observed here. Relatively poor performance for temporal selection may reflect a similar underlying cause. Greater difficulties in allocating attentional resources over time in the central field may result in slower 'attentional waking' (Ariga and Yokosawa, 2008) and thus may explain poorer target identification in these tasks as well as in the CPT.

3.2. Reconciling deficit and enhancement views

To better understand which aspects of attention are modified by early deafness we have argued that the same subjects should be studied under a variety of attentional tasks. The same deaf and hearing children and adults assessed on the RSVP and AB tasks were also tested using a variant of the Useful Field of View (UFOV; Ball and Owsley, 1993) to determine how their attention was distributed across central and peripheral regions of the visual field. This UFOV task was designed to be child-friendly and minimize task demands above and beyond attentional processing.

The UFOV is a visual search task with a concurrent central identification task. It requires attention to be allocated both centrally and peripherally, while also selecting the target from distractors in the periphery. It therefore concurrently taxes divided attention skills and attentional selection in space. Using this task, enhanced performance has been documented in deaf adults, whereby deaf adults maintain 79% accuracy with shorter display durations than their hearing peers. This result has been attributed to enhanced attention to the periphery resulting from a redistribution of attention across the visual field as a consequence of early auditory deprivation (the use of a sign language has little-or-no impact upon UFOV task performance). In the data reported here, the same deaf children that were at risk on the selection of a target in an RSVP stream did not differ from their hearing peers on this spatial selection task. If anything, there is a trend for the deaf children to outperform the hearing children on this task (Fig. 6).

Thus, while Quittner and colleagues have argued that there are visual selective attention deficits resulting from early auditory deprivation, we note that deaf children are not at a disadvantage on all attentional tasks. Moreover, by adulthood, deaf individuals, at least those that have had early access to a natural language, do not exhibit attentional deficits. Quite to the contrary, some aspects of selective attention are enhanced in this population (Bavelier et al., 2006; Bavelier and Neville, 2002; Dye et al., 2009). This highlights the high degree of specificity observed in cross-modal plastic changes resulting from early auditory deprivation. Attempts to characterize changes in visual attention skills following early deafness must be careful in determining which aspects of visual attention are susceptible to alteration. Furthermore, it is important to try and separate the effects of deafness from the possible effects of altered social and linguistic environments. Here we show that apparent temporal attention deficits in a population exposed early to a signed language appear to be ameliorated by adulthood. Hand-in-hand with this, the spatial compensation noted in deaf adults is only at best weakly present in young deaf children.

3.3. Concluding remarks

We have illustrated how by testing the same group of deaf and hearing individuals on various aspects of visual attention, a striking pattern of attentional advantages and deficits can be revealed as a consequence of early deafness. Far from revealing a general deficit in selective attention in deaf participants, this approach highlights different strengths and weaknesses depending on the aspects of attention tested and the age of the participants. Whereas selective attention in time appears to be challenged in deaf children, selective attention in space appears to be on par with that of hearing children. By adulthood, the deficit in temporal selection noted in deaf children has by-and-large resolved

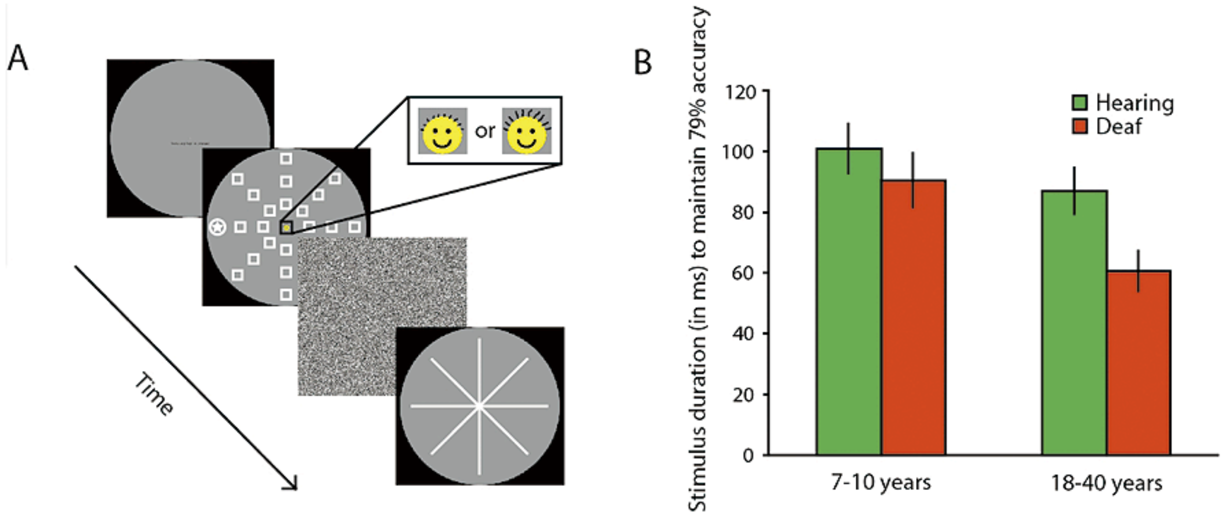

Fig. 6. A. In the Useful Field of View tasks, participants are presented with a central target to be identified (a smiley face with long or short hair) and a peripheral target to be localized (a five-pointed star enclosed in a circle) that can be presented at one of eight locations. These concurrent targets are accompanied by distractors (squares) that the participant is instructed to ignore. B. Using an adaptive staircase procedure, the stimulus duration is reduced until participants reach 79.3% accuracy in central target identification and concurrent peripheral target localization. For the 7–10 year olds, there is no significant difference between the thresholds of deaf ($n = 8$) and hearing ($n = 40$) children. In 18–40 year olds, deaf adults ($n = 14$) have a clear advantage over hearing adults ($n = 19$), on average requiring 25% less time to succesfully process both central and peripheral targets.

itself and deaf individuals are seen to outperform their hearing peers when selection in space is tested. This pattern of behavior illustrates that it is not the case that deaf individuals suffer from greater distractibility and a general inability at focusing attention. They are clearly challenged early in life by tasks that require temporal selection. Yet, even in this domain, not all aspects of selection in time are compromised. In contrast to a clear difficulty when asked to select a first target in a fast stream of stimuli, deaf children show similar abilities in selecting and processing a second, subsequent target. This intact skill reveals spared recovery of attention over time and suggests that the initial deficit may be best understood as a poor ability at initially allocating attention toward a stream of stimuli presented at a fast pace in a specific spatial location: the center of the visual field. The deficit in attentional selection in time found in deaf children is therefore quite specific; how specific remains unknown. For example, it is unclear whether a similar deficit would be noted if stimuli were to be presented not just centrally, but at separate peripheral locations over time.

We recognize that this study is both preliminary and exploratory, with a small sample of deaf children. Further work is needed to document the time course of temporal and spatial components of attentional changes in both deaf and hearing individuals. The field is also in need of more longitudinal studies to ensure that cohort differences are due to factors such as length of sensory deprivation and not sampling differences that can cloud the interpretation of cross-sectional studies. It will also be interesting to investigate further the effects of sensory restitution via cochlear implantation. Here it will be important to use adequate control group designs, for example comparing implanted and unimplanted deaf children who were all considered to be good candidates for cochlear implantation surgery. It will also be essential to control for, or at least carefully document, possible differences in early language, social and educational experiences that may have an impact upon the development of visual attention skills in these groups of children. Such studies will shed invaluable light on the status of attention as a function of not only early deafness but also early language experience.

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References

Ariga, A. & Yokosawa, K. (2008). Attentional awakening: Gradual modulation of temporal attention in rapid serial visual presentation. *Psychological Research, 72*, 192-202.

Ball, K.K. & Owsley, C. (1993). The useful field of view test: A new technique for evaluating age-related declines in visual function. *Journal of the American Optometric Association, 64*(1), 71-79.

Bavelier, D. & Neville, H. J. (2002). Cross-modal plasticity: Where and how? *Nature Reviews Neuroscience, 3*(6), 443-452.

Bavelier, D., Tomann, A., Hutton, C., Mitchell, T. V., Corina, D. P., et al., (2000). Visual attention to the periphery is enhanced in congenitally deaf individuals. *The Journal of Neuroscience, 20*(17), RC93.

Bavelier, D., Brozinsky, C. J., Tomann, A., Mitchell, T. V., Neville, H. J., et al., (2001). Impact of early deafness and early exposure to sign language on the cerebral organization for motion processing. *The Journal of Neuroscience, 21*(22), 8931-8942.

Bavelier, D., Dye, M.W.G. & Hauser, P.C. (2006). Do deaf individuals see better? *Trends in Cognitive Sciences, 10*(11), 512-518.

Bosworth, R.G. & Dobkins, K.R. (2002). The effects of spatial attention on motion processing in deaf signers, hearing signers, and hearing nonsigners. *Brain and Cognition, 49*(1), 152-169.

Bottari, D., Turatto, M., Bonfioli, F., Abbadessa, C., Selmi, S., Beltrame, M.A., et al., (2008). Change blindness in profoundly deaf individuals and cochlear implant recipients. *Brain Research, 1242*, 209-218.

Chun, M.M. & Potter, M.C. (1995). A two-stage model for multiple target detection in rapid serial visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 109-127.

Dye, M.W.G., Baril, D.E. & Bavelier, D. (2007). Which aspects of visual attention are changed by deafness? The case of the Attentional Network Test. *Neuropsychologia, 45*(8), 1801-1811.

Dye, M.W.G., Hauser, P.C. & Bavelier, D. (2009). Is visual attention in deaf individuals enhanced or deficient? The case of the Useful Field of View. *PLoS ONE, 4*(5), e5640. doi:10.1371/journal.pone.0005640.

Finney, E.M., Fine, I. & Dobkins, K.R. (2001). Visual stimuli activate auditory cortex in the deaf. *Nature Neuroscience, 4*(12), 1171-1173.

Green, C.S. & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature, 423*(6939), 534-537.

Hauser, P.C., Dye, M.W.G., Boutla, M., Green, C.S. & Bavelier, D. (2007). Deafness and visual enumeration: Not all aspects of attention are modified by deafness. *Brain Research, 1153*, 178-187.

Horn, D.L., Davis, R.A., Pisoni, D.B. & Miyamoto, R.T. (2005). Development of visual attention skills in prelingually deaf children who use cochlear implants. *Ear and Hearing, 26*(4), 389-408.

Loke, W.H. & Song, S. (1991). Central and peripheral visual processing in hearing and nonhearing individuals. *Bulletin of the Psychonomic Society, 29*(5), 437-440.

Neville, H.J. & Lawson, D. (1987a). Attention to central and peripheral visual space in a movement detection task: An event-related potential and behavioral study. I. Normal hearing adults. *Brain Research, 405*, 253-267.

Neville, H.J. & Lawson, D. (1987b). Attention to central and peripheral visual space in a movement detection task: An event-related and behavioral study. II. Congenitally deaf adults. *Brain Research, 405*, 268-283.

Neville, H.J. & Lawson, D. (1987c). Attention to central and peripheral visual space in a movement detection task. III. Separate effects of auditory deprivation and acquisition of a visual language. *Brain Research, 405*, 284-294.

Olivers, C.N. & Nieuwenhuis, S. (2006). The beneficial effects of additional task load, positive affect, and instruction on the attentional blink. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 364-379.

Parasnis, I. & Samar, V.J. (1985). Parafoveal attention in congenitally deaf and hearing young adults. *Brain and Cognition, 4*(3), 313-327.

Pascual-Leone, A., Amedia, A., Fregni, F. & Merabet, L. (2005). The plastic human brain cortex. *Annual Review of Neuroscience, 28*, 377-401.

Peterson, C.C. & Siegal, M. (2002). Representing inner worlds: Theory of mind in autistic, deaf, and normal hearing children. *Psychological Science, 10*, 126-129.

Proksch, J. & Bavelier, D. (2002). Changes in the spatial distribution of visual attention after early deafness. *Journal of Cognitive Neuroscience, 14*(5), 687-701.

Quittner, A.L, Smith, L.B., Osberger, M.J., Mitchell, T. & Katz, D. (1994). The impact of audition on the development of visual attention. *Psychological Science, 5*, 347-353.

Quittner, A.L., Barker, D., Snell, C., Cruz, I., McDonald, L., et al., (2007). Improvements in visual attention in deaf infants and toddlers after cochlear implantation. *Audiological Medicine, 5*, 242-249.

Raymond, J.E., Shapiro, K.L. & Arnell, K.M. (1992). Temporary suppression of visual processing in an RSVP task: An attentional blink? *Journal of Experimental Psychology: Human Perception and Performance, 18*(3), 849-860.

Raymond, J.E. (2003). New objects, not new features, trigger the attentional blink. *Psychological Science, 14*(1), 54-59.

Rettenbach, R., Diller, G. & Sireteanu, R. (1999). Do deaf people see better? Texture segmentation and visual search compensate in adult but not in juvenile subjects. *Journal of Cognitive Neuroscience, 11*(5), 560-583.

Röder, B., Rösler, F., Henninghausen, E. & Näcker, F. (1996). Event-related potentials during auditory and somatosensory discrimination in signted and blind human subjects. *Cognitive Brain Research, 4*(2), 77-93.

Sadato, N. (2005). How the blind see Braille: Lessons from functional magnetic resonance imaging. *The Neuroscientist, 11*(6), 577-582.

Shapiro, K.L. & Garrad-Cole, F. (2003). Age-related deficits and involvement of frontal cortical areas as revealed by the attentional blink task [Abstract]. *Journal of Vision, 3*(9), 726a, http://journalofvision.org/3/9/726/, doi:10.1167/3.9.726.

Shin, M.S., Kim, S.K., Kim, S.S., Park, M.H., Kim, C.S. & Oh, S.H. (2007). Comparison of cognitive function in deaf children between before and after cochlear implant. *Ear and Hearing, 28*(2 Suppl.), 22S-28S.

Sladen, D.P., Tharpe, A.M., Ashmead, D.H., Wesley Grantham, D. & Chun, M.M. (2005). Visual attention in deaf and normal hearing adults: effects of stimulus compatibility. *Journal of Speech, Language, and Hearing Research, 48*(6), 1529-1537.

Smith, L.B., Quittner, A.L., Osberger, M.J. & Miyamoto, R.T. (1998). Audition and visual attention: The developmental trajectory in deaf and hearing populations. *Developmental Psychology, 34*(5), 840-850.

Stevens, C. & Neville, H.J. (2006). Neuroplasticity as a double-edged sword: deaf enhancements and dyslexic deficits in motion processing. *Journal of Cognitive Neuroscience, 18*(5), 701-714.

Visser, T.A., Davis, C. & Ohan, J.L. (2009). When similarity leads to sparing: Probing mechanisms underlying the attentional blink. *Psychological Research, 73*, 327-335.