Literature Review

Spatial and temporal cognition: Abilities and deficits following hearing loss

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INTRODUCTION

Spatial processes, understanding the position of objects in the world and the relationships and transformations of these objects (Emmorey, Damasio, McCullough, Grabowski, Ponto et al., 2002), and temporal processes, identifying the timing, order, and sequence of stimuli (Nava, Bottari, Zampini & Pavani, 2008) are systems that are uniquely tied to specific modalities. The auditory modality has been shown to perceive temporal information more accurately than the visual system, which in turn is more conditioned for processing spatial information. As stated by the modality appropriateness hypothesis (Welch & Warren, 1980) when a stimulus of two or more sensory modalities is presented the modality with greater resolution will have a stronger affect on the percept than the modality with the lesser resolution—vision has a stronger resolution for spatial stimuli and hearing for temporal stimuli. Kubovy (1988) indicates that space is the provision of vision, vision is not inherently temporal, audition is intimately tied to time, and that audition is not spatial. Adhering to this analogy of space:time::vision:audition it can be proposed that spatial cognition may be improved following deafness given the contributions of the visuo-spatial components of sign language and heightened visual systems and that temporal cognition may be impaired due to the lack of audition which predominates temporo-sequential processing. The link of space to vision and time to audition is an important factor in how hearing loss can differently affect processes that are based in separate modalities. As areas that respond to visual stimuli expand in the brain spatial processes may be enhanced while temporal processing may be diminished due to the lack of a hearing modality.

Following will be a review of the spatial and temporal processing in deafness. This literature review will discuss both the evidence of enhanced spatial abilities after hearing loss and its relation with sign languages along with the nature of temporal and sequential deficits in deafness.

DEAFNESS, SIGN LANGUAGES, AND SPATIAL PROCESSING

In lieu of verbal communication deaf persons use sign language which relies heavily on arbitrary hand shapes, palm orientations, locations, movements, spatial relations among signs, and sign order (Rönnberg, Söderfeldt, & Risberg, 2000). Clearly the use of space is unique in sign language. Signing space is the term used for the three-dimensional space in front of the signer and functions topographically to represent spatial relations among objects (Emmorey et al., 2002). To describe spatial relationships signers use classifier constructions to indicate the movement and location of objects in space rather than prepositions (Emmorey, Kosslyn, & Bellugi, 1993). This scheme uses actual space itself to communicate spatial information and such spatial information is layered within one sign (Emmorey et al., 1993). An additional unique use of space in sign languages (SL) is that spatial relationships are mentally represented as the reverse of what the addressee actually observes. Therefore, to understand the scene from the perspective of the signer, the addressee must mentally reverse the spatial locations that the addressor is signing by using mental imagery generation, maintenance, and rotation (Emmorey et al., 1993). The spatial properties of sign languages lead to the hypothesis that fluent signers could be facilitated in spatial processing and representation. However, it has also been hypothesized that enhanced spatial processing could be caused by sensory deprivation following hearing loss and the cortical reorganization that accompanies that. Faster visual processing and enhanced spatial memory are just two areas where deaf individuals out performed hearing signers and hearing non-signers. Still debated, however, is the root of these spatial enhancements and which hypothesis best explains these cognitive changes—is it due to hearing loss (auditory deprivation hypothesis) or a familiarity with a spatial language (sign language hypothesis)?

Emmorey et al. (1993) has provided evidence for the sign language hypothesis by testing deaf signers of ASL, hearing signers who have deaf parents, and hearing non-signers as participants in order to investigate imagery abilities. As image generation, maintenance, and transformation are integral to ASL production it was hypothesized that signers would be better at these aspects of imagery. Image generation consists of visual mental images that are actually constructed from various stored visual information and image maintenance tested how well participants could hold an image in short-term memory. A fundamental aspect of ASL is placing loci in signing space and then referring back to those loci throughout the conversation, which may lead to enhanced visual short-term memory for signers. Finally, mental rotation is used when comparing forms that may differ in subtle ways, for example a form and its mirror reversal. This is vital to ASL communication because the addressee must make use of reversal transformations when receiving information from the speaker. Emmorey et al. (1993) found enhanced performance on image generation and image rotations (specifically evaluating mirror reversals) by ASL signers (hearing and deaf) over non-signers, suggesting that this performance was due to experience with sign language rather than being accounted for by auditory deprivation. However, increased accuracy in the mental rotation task was found for deaf signers over hearing signers which indicates an improvement due to deafness.

Further support for the sign language hypothesis comes from a series of studies that investigated how well deaf signers, hearing signers, and hearing non-signers could remember different pictures such as faces and shoes (Arnold & Murray, 1998). Arnold and Murray (1998) investigated visual spatial memory with a matching pairs game paradigm and found that deaf signers performed better on face recall than hearing signers (who were significantly better than hearing non-signers), while performance on object recall was comparable for both the deaf and hearing groups. They concluded that deafness and the long-term use of sign language had additive effects on performance of the face task. Arnold and Mills (2001) furthered this research to investigate whether this effect was exclusive to faces or whether the deaf and hearing signer's superior recall extends to other complex three-dimensional objects, such as shoes. Results indicated that, in terms of the numbers of turns required, shoes are remembered in a similar way to human faces and neither of which are like simple nameable objects. Deaf and hearing signers performed similarly and both outperformed hearing non-signers in the face task and the shoe task, but the two signing groups did not significantly differ from each other. These results further suggest the superior performance of the signing groups was a reflection of familiarity with sign language rather than due to a lack of an auditory modality. Conjecture as to the root of this superior performance has led to the hypothesis that communicating in sign language demands the signee to retain long visual sequences of hand shapes, face, and body shape movement in working memory and this may be useful in remembering where the complex pictures are located in the matching pairs game.

Contrarily, confirmation of the auditory deprivation hypothesis has also been demonstrated. In order to study the cross-modal interactions and recruitment of cortical areas following hearing loss and possible enhancements to visual search behavior as a result of deafness Stivalet, Moreno, Richard, Barraud, and Raphel (1998) examined if there were differences in visual search task performance between deaf and hearing adults. Previously, behavioral data has shown that deaf subjects detect the direction of motion faster and more accurately than hearing subjects when the stimuli are presented in the peripheral visual field (Neville & Lawson, 1987). Researchers (Stivalet et al., 1998) used a visual search task in order to confirm whether this advanced processing occurs in the central in addition to the peripheral visual field. A visual search paradigm was used which allowed researchers to identify whether parallel (pre-attentive) or serial (requiring attention) visual search occurred when searching for a target among distracters. Search time analysis results indicated that deaf subjects showed parallel processing, or a pop-out effect, while hearing subjects exhibited serial processing. A pop-out effect indicates that search times were not effected by an increase in the number of distracters. This suggests that deaf adults develop more efficient visual processes than normal hearing adults in the central visual field.

Deaf signers were significantly faster than hearing non-signers and hearing native signers in identifying the direction of motion of a peripheral target (Neville & Lawson, 1987a, 1987b, 1987c) which does suggest enhanced performance due to auditory deprivation. Bavelier et al. (2000) confirmed this auditory deprivation hypothesis with compelling functional magnetic resonance imaging (fMRI) research which indicated that following hearing loss attentional resources are reorganized from central space to peripheral space. This was tested by presenting hearing controls and hearing signers and deaf native signers with distracters that were either centrally located or peripherally located; neural activity ratios showed that deaf individuals had greater distractibility from the peripheral distracters while both hearing groups were distracted from centrally presented distracters. These findings indicate that it was an effect from deafness, not sign language use, which caused the enhanced distribution of attentional to the periphery in deaf native signers.

Cattani and Cibbens (2005) investigated visuo-spatial memory in deaf, signers and non-signers, and hearing, signers and non-signers, and their ability to remember the location of either objects or abstract images. Mean reaction times were measured and deaf signers performed significantly faster than hearing non-signers in their ability to remember the spatial location of an object. Furthermore, both deaf signers and non-signers were more accurate than hearing non-signers when recalling the location of a picture. This finding suggests that deafness, not sign language, was the root of the enhanced memory for location in deaf participants.

The evidence presented has shown that there is a significant enhancement to spatial processing following hearing loss. Deaf signers are able to perceive peripheral stimuli better, generate and transform images faster, and have more efficient visual search. Evidence has supported both the auditory deprivation hypothesis as well as the sign language hypothesis as the cause of the improved spatial processing in deaf people. However, these two hypotheses are not mutually exclusive and together they explain for the superior performance by deaf signers on multiple spatial tasks. Research with deaf signers, hearing signers, and hearing non-signers have highlighted this claim such that deaf signers outperformed hearing signers and non-signers on spatial memory tasks (Arnold & Murray 1998). Depending on the spatial task it seems either deafness or sign language can account for the enhanced spatial processing. For visual search, stimuli detection, and mental rotation tasks deafness accounts for enhanced performance, while for image maintenance and generation, and memory for location of objects was helped by the use of sign. Nonetheless, deaf signers consistently performed better than hearing non-signers.

DEAFNESS AND TEMPORAL PROCESSING

Vision, audition, and touch to work together in order to accurately acquire different forms of information from the world around us (Conway, Pisoni & Kronenberger, 2009). Audition in particular seems to play a special role in processing temporal and sequential signals which are of vital importance for the understanding of serially ordered events (Conway, Pisoni & Kronenberger, 2009). Audition is the core of the newly developing "scaffolding hypothesis" which states that sound provides a supporting framework for interpreting and processing sequential information. Hearing is one of the basics of perception, acting as a framework for the development of sequential processing and behavior. Following auditory deprivation cognitive and perceptual sequencing skills related to time, serial order, and serial recall may be delayed or reorganized (Conway, Pisoni and Kronenberger, 2009). The scaffolding hypothesis is a useful tool that emphasizes the bootstrapping characteristic of sound and the vital role it plays in the development of cognitive processes that rely on encoding, learning, and manipulation of information that occur in sequence.

The lack of auditory stimulation has been postulated to cause a deficit in temporal processing due to the fact that the auditory modality exceeds the visual modality in detection of temporal change (Poizner & Tallal, 1987). Heming and Brown (2005) investigated tactile and visual temporal processing for deaf and hearing subjects. Researchers found that the visual temporal threshold, the amount of time that separates the onset of two sensory stimuli when they are judged as simultaneous by the subject, were significantly higher for deaf persons than hearing controls. In fact, the deaf participants' (18-31 years old) visual temporal thresholds was comparable to that of healthy 60-80 year olds and for every block of trials deaf participants' visual temporal thresholds were consistently higher than their age-matched hearing control. This indicates that hearing loss significantly impedes the ability to time tactile and visual information demonstrating that functional brain reorganization following hearing loss has differential and complex effects on the perceptual abilities of the spared senses (Heming & Brown, 2005).

Evidence of an auditory dominance for temporal processing has come from a direct comparison between modalities in a temporal task. Conway and Christiansen (2005) presented three groups of hearing participants with auditory, visual, or tactile sequential patterns and, once calculating for chance performance, auditory learning accounted for twice as much learning over tactile and visual information. A similar sequential learning task was conducted with hearing and deaf children. A learning score was used to measure to sequence memory span improvement. Results showed that the normal-hearing children's learning score was significantly greater than that of deaf children, who on average showed no learning. These findings indicate that if a period of deafness occurs during early development secondary disruptions occur to non-auditory sequencing skills.

Duration judgment is another aspect of temporal processing. Kowalska and Szelag (2006) investigated the effect of auditory deprivation on deaf and hearing control's abilities to judge the duration of visual stimuli in the range of seconds. Both production and reproduction methods were used which allowed the researchers to assess the influence of each task on temporal estimation. Results indicated that deaf participants consistently and significantly overestimated the intervals of short standards compared to normal hearing adults and this may be due to factors that occur following hearing loss such that attentional resources may be distributed differently.

Contrary to these findings Nava et al. (2008) found faster discrimination responses for deaf participants when distinguishing temporal order judgments. Researchers (Nava et al., 2008) sought to examine whether the compensatory cortical reorganization that occurs after hearing loss extends to temporal processing abilities or if the auditory system so finely processes temporal events that the visual system cannot possibility compensate for it. The study was designed to examine whether the location of targets in the visual field can modulate temporal processing in the millisecond range for deaf and hearing participants. Results indicated that deaf are not impaired in temporal order judgments in the millisecond range. These findings were contrary to those of Heming and Brown (2005) and Kowalska and Szelag (2006), and Nava et al. (2008) explains that this discrepancy is due to the two different tasks that were used: the simultaneity judgment task and temporal order judgment task; and that these paradigms may involve somewhat different aspects of temporal perception. Rudner, Andin, and

Rönnberg (2009) examined working memory in deaf and hearing populations and highlighted a finding in which deaf participants performed equally as well as hearing participants in item recall, but significantly poorer in recall of the order of the items. Nava et al. (2008) stated that rather than there being an overall deficit of temporal processing for deaf persons, perhaps there is a selective difficulty when judging simultaneity of visual events and temporal recall.

The increased use of spatial cues in signed languages can affect linguistic and non-linguistic aspects of cognition. A reduced short term memory capacity has been repeatedly shown in the serial recall of signs. Short term memory is the ability to hold information in mind for a few seconds and it is thought to be limited to 7 items +/- 2 (Miller, 1956). However, deaf ASL users exhibited a mean span of 4.4 and ASL/English bilinguals had a mean ASL memory span of 5.2 and an English memory span of 7.05 (Boutla et al., 2004). From the design used in this experiment Boutla et al. (2004) were able to conclude that this difference was not attributed to phonological factors, item duration or reduced memory abilities in deaf people. Instead they concluded that the spoken span of 7 +/- 2 is an exception due to the reliance of speakers on auditory-based rather than visually based representations. Further, it has been proposed that signers and speakers may encode information quite differently; speakers relying on temporal encoding and singers on spatial encoding. Such that the difference in short term memory span may partly arise from the demands of the task which requires recall in serial order with little spatial patterning (Boutla et al., 2004).

Due to the distinctive link of sequential and temporal processing to audition these processes are significantly hindered following hearing loss. The evidence presented has shown that deaf persons, due to the lack of a hearing modality and the inability for sound to act as a framework for developing these cognitive processes, are poorer at determining judgment durations and temporal order judgments in the non-millisecond range. Interestingly, temporal order judgment abilities differed depending on the time range, such it is proposed that there may be a selective rather than an overall deficit. Without the framework of sound sequential, temporal and serial processing is hindered in deaf persons.

CONCLUSION

This review has illustrated the current evidence that the absence a hearing modality can lead to enhanced spatial abilities, such as memory and mental rotation, however a deficit in temporal and pattern recognition can occur as well. These effects are due to the strong linkage of space to vision and time to audition. Important to disclose is the influence that age of hearing loss onset may have on these enhancements and deficits. Brain organization for languages relies heavily on sensitive periods of development important for perception, production, and left-hemisphere specialization of language. Early use of sign language has not only contributed to the enhancement of spatial cognition and memory, but also to social functions and theory of mind abilities fundamental to proper child development (Rönnberg et al., 2000). Age of onset of sensory deficit cannot be controlled in humans and thus findings from the articles cited in this literature review have collapsed results across multiple studies in which age of onset and completeness of deafness varied. Though, the magnitude of spatial improvement and temporal deficit could differ with age of onset of hearing loss it has been shown that despite these population variations such enhancements and deficits are shared.

The four populations used in he cited studies consisted of hearing non-signers, hearing signers, deaf non-signers, and deaf signers. Testing these populations permits exploration into the dissociation between deafness and use of sign language and whether enhancement in spatial cognition was due to auditory deprivation or due to the familiarity with a spatial language. It is important to interpret the findings according to the population tested to ensure that you are not giving credit to deafness when the use of sign language accounted for the observed enhancement.

Future research should further examine the dissociation between spatial language and auditory deprivation and the influence of each on spatial processing in deaf persons. Additionally, the scaffolding hypothesis by Conway, Pisoni and Kronenberger (2009) has recently been introduced and it would be interesting to examine the other tasks that audition provides support for and how deprivation would affect these processes.

In conclusion this literature review has highlighted the existing research on the spatial abilities of deaf people and deficits in temporal and sequential processing, identifying the influence of sign language and the intricate link of vision to space and audition to time. It has been shown that there is better spatial performance in deaf persons, however the root of this performance is still debated. Some researchers (Bavelier et al., 2001; Cattani & Cibbens, 2005; Stivalet et al., 1998) have found that the uniqueness of being deaf is the primary reason for the enhanced performance while evidence others (Arnold & Murray, 1998; Emmorey et al., 1993) point towards the use of a spatial language as improving spatial processing. What can be firmly concluded is that deaf signers outperform hearing non-signers on spatial tasks. Alternatively, following hearing loss, there is poorer temporal and sequential performance. This is due to the fact that timing is intimately tied to audition which acts as a cognitive sequencer. Support from the scaffolding hypothesis lends the explanation that audition is necessary to process temporal information as it acts as a framework for the development of sequential processing and behavior. Understanding the enhancements and deficits that can occur following hearing loss is important in order to understand cortical reorganization following hearing loss, additionally it is important to highlight that being deaf is typically considered a disadvantage or handicap, when in fact, as this review has shown, superior performance for spatial tasks can accompany deafness as well. This literature review has revealed how the lack of a hearing modality can lead to superior spatial processing while impairing temporal and sequential processing in the deaf population.

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