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The Sign Superiority Effect: Lexical Status Facilitates Peripheral Handshape Identification for Deaf Signers

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Deaf signers exhibit an enhanced ability to process information in their peripheral visual field, particularly the motion of dots or orientation of lines. Does their experience processing sign language, which involves identifying meaningful visual forms across the visual field, contribute to this enhancement? We tested whether deaf signers recruit language knowledge to facilitate peripheral identification through a *sign superiority effect* (i.e., better handshape discrimination in a sign than a pseudosign) and whether such a superiority effect might be responsible for perceptual enhancements relative to hearing individuals (i.e., a decrease in the effect of eccentricity on perceptual identification). Deaf signers and hearing signers or nonsigners identified the handshape presented within a static ASL fingerspelling letter (Experiment 1), fingerspelled sequence (Experiment 2), or sign or pseudosign (Experiment 3) presented in the near or far periphery. Accuracy on all tasks was higher for deaf signers than hearing nonsigning participants and was higher in the near than the far periphery. Across experiments, there were different patterns of interactions between hearing status and eccentricity depending on the type of stimulus; deaf signers showed an effect of eccentricity for static fingerspelled letters, fingerspelled sequences, and pseudosigns but not for ASL signs. In contrast, hearing nonsigners showed an effect of eccentricity for all stimuli. Thus, deaf signers recruit lexical knowledge to facilitate peripheral perceptual identification, and this perceptual enhancement may derive from their extensive experience processing visual linguistic information in the periphery during sign comprehension.

Public Significance Statement

Deaf signers demonstrate an ability to process visual information in the periphery more effectively than their hearing counterparts. It is important to know whether aspects of this enhanced ability is associated with experience processing sign language. Evidence that this is the case would suggest that sign language (e.g., American Sign Language, ASL) provides benefits to cognitive processing that could extend to other complex visuo-linguistic processing tasks such as reading in a second language (e.g., English). Thus, this research has potential to inform deaf education policy by adding to our knowledge of the importance of sign language in cognitive development and academic success for deaf individuals.

Keywords: peripheral perception, lexical status, deafness, sign language

Deaf signers have well-documented peripheral processing enhancements relative to hearing nonsigners for simple visual information such as the location or movement of dots (see Dye & Bavelier, 2013). It has been hypothesized that the source of these perceptual enhancements is likely tied to deafness (see Stoll & Dye, 2019), which may lead to plastic changes in the dorsal "where" pathway of visual processing (Neville & Lawson, 1987b). However, identification of visual form is supported by the ventral "what" pathway, which may be distinct from knowing where the form is or where it is moving (Ungerleider & Mishkin, 1982). Thus, while deafness may lead to enhanced reactivity to visual events rather than enhanced perceptual representations (Pavani & Bottari, 2012), experience processing sign language may lead to changes associated with discriminating visual forms in the periph-

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ery. If this is the case, peripheral discrimination of visual forms should be enhanced for deaf signers, but only when a) the stimuli are moving, due to dorsal pathway enhancements as a consequence of deafness, and/or b) when the stimuli are linguistically meaningful, due to ventral pathway enhancements as a consequence of sign language knowledge. Because no extant research has tested the contribution of linguistic meaningfulness of visual stimuli to peripheral sign language identification, we tested deaf signers' ability to discriminate American Sign Language (ASL) handshapes at near and far eccentricities when those handshapes were embedded in static images and moving sequences that were either linguistically meaningful or not meaningful.

Peripheral Perceptual Enhancements for Deaf Relative to Hearing Individuals

There is ample evidence that, for peripherally presented stimuli, deaf individuals allocate attention more effectively than hearing individuals for low-level perceptual properties of visual stimuli (Bavelier et al., 2001; Dye, Baril, & Bavelier, 2007; Neville, & Lawson, 1987a, 1987b) and show greater activation of brain areas related to attentional control and movement processing (e.g., the posterior parietal cortex and motion-selective area; Dye & Bavelier, 2010; Bavelier et al., 2000). Deaf individuals' peripheral processing enhancement may be observed only when attention is necessary to manage processing between multiple locations. For example, there are no differences between deaf and hearing individuals in basic perceptual abilities including visual acuity, sensory thresholds for brightness, and contrast sensitivity (Finney & Dobkins, 2001), or when assessing the direction of motion of objects on a screen in central vision (Bosworth & Dobkins, 2002). However, deaf individuals do respond faster and more accurately than hearing individuals to peripheral targets, especially when central distractors are present and selective attention is required (Bavelier, Dye, & Hauser, 2006; Bosworth & Dobkins, 2002; Bottari, Nava, Ley, & Pavani, 2010; Dye et al., 2007, 2009; Neville & Lawson, 1987c; Parasnis & Samar, 1985). In contrast, hearing individuals show greater focus on central vision and impairments for central distractors relative to deaf individuals (Stevens & Neville, 2006). Thus, in terms of peripheral perceptual processing, deaf individuals show enhanced abilities across a range of tasks and stimuli (Dye & Bavelier, 2013; Pavani & Bottari, 2012).

Peripheral Perceptual Enhancements for Sign Language Users

Although some have argued that the redistribution of attention in deaf signers is a compensatory mechanism in response to auditory deprivation (Chen, He, Chen, Jin, & Mo, 2010; Bola et al., 2017), other research suggests it is also the result of experience with a visual language. Relative to hearing nonsigners, deaf signers show improved mental rotation ability (Boutla, Supalla, Newport, & Bavelier, 2004; Emmorey, Klima, & Hickok, 1998), image generation (Wilson, Bettger, Niculae, & Klima, 1997), and facial recognition (Arnold & Murray, 1998; Bettger, Emmorey, McCullough, & Bellugi, 1997; see Stoll et al., 2018). Importantly, nonsigning deaf children do not show the same advantages (Parasnis, Samar, Bettger, & Sathe, 1996; Wilson et al., 1997). Thus, enhanced visual spatial skills found in deaf signers are not exclusive to being deaf, but partially arise from experience with a visual language.

There is reason to believe that sign language experience may contribute to peripheral processing enhancement specifically associated with visual form discrimination (Stoll & Dye, 2019). These enhancements may arise because sign language comprehension requires simultaneous identification of linguistically informative visual forms in central vision (i.e., facial expression, which modifies the meaning of manual signs) and peripheral vision (i.e., handshape, which distinguishes two manual signs from one another; see Dye, 2016; Stoll & Dye, 2019). Sign comprehenders tend to fixate the signer's face to recognize facial expression (Agrafiotis, Canagarajah, Bull, & Dye, 2003; Emmorey, Korpics, & Petronio, 2009; Mastrantuono, Saldaña, & Rodríguez-Ortiz, 2017; Muir & Richardson, 2005) while the majority of manual signs are produced far away from fixation (e.g., on average of 6.5° away from the eyes in ASL narratives; Bosworth, Wright, & Dobkins, 2019). Therefore, deaf signers have a lifetime of experience managing visual attention between central and peripheral vision to perform linguistically relevant perceptual identification. Indeed, Stoll and Dye (2019) found that sign language experience did enhance the ability to discriminate between simple visual forms (i.e., the orientation of lines) presented in the periphery, but only for items presented below fixation, not above, aligning with the fact that most signs are produced in this inferior visual field. However, little research has investigated peripheral discrimination of meaningful visual forms, such as those used in sign language. Therefore, the current study investigates deaf signers' ability to discriminate visual stimuli from ASL in the periphery to assess the role of visual language in the reorganization of visual processing systems.

Sign language may have an even larger role on the reorganization of visual processing systems when visual form discrimination is linguistically meaningful. In fact, deaf signers show advantages relative to hearing nonsigners in peripheral processing for reading static text, suggesting that they not only detect motion or discriminate visual features more efficiently, but they are also more efficient at peripherally processing linguistically meaningful stimuli in their second language. For example, skilled deaf readers have a wider perceptual span during English sentence reading relative to hearing nonsigners who read at an equivalent comprehension level (Bélanger, Slattery, Mayberry, & Rayner, 2012). These enhancements are observed even in children aged 7–15 years (Bélanger, Lee, & Schotter, 2018), suggesting that the enhancements may arise prior to complete development of the reading system, perhaps as a consequence of experience identifying linguistic forms in peripheral vision during sign language comprehension. If deaf signers show an enhanced ability to identify and discriminate meaningful linguistic ASL stimuli in the periphery relative to hearing nonsigners, this would provide evidence that experience with a visual language influences perceptual abilities beyond simple motion detection and other low-level enhancements that could be attributable to deafness. In addition, such findings would provide preliminary evidence that the enhanced perceptual span for deaf readers may relate to their experiences identifying linguistic information in peripheral vision through their primary signed language. We propose that, although many signs are perceived in the inferior visual field, processing advantages for linguistic stimuli likely extend to the left-right periphery as well.

Word Superiority and Its Influence on Peripheral Perception

Although the decrease in efficacy of peripheral vision is more dramatic for distinguishing visual form than for detecting visual motion (Aristis, 1986 as cited in Swisher, Christie, & Miller, 1989), hierarchical knowledge about how visual forms are meaningfully combined (i.e., language knowledge) may lead to enhanced perception in the periphery. In fact, among hearing individuals it has been shown that letter discrimination is better when the letter is embedded in a meaningful stimulus (e.g., a word) than when it is embedded in a meaningless stimulus (e.g., a nonword) or when it is presented alone. This phenomenon is referred to as a *word superiority effect* (Cattell, 1886; Reicher, 1969; Wheeler, 1970) and it suggests that lexical status can facilitate low-level perceptual discrimination (i.e., of a component letter). Additionally, although presenting stimuli in the periphery leads to a decrease in letter discrimination accuracy, lexical status mitigates the effect of eccentricity on letter identification such that it is smaller when the letter is embedded in a word than when it is embedded in a nonword (Bouma, 1973; Jordan, Patching, & Thomas, 2003). Thus, a meaningful linguistic context enhances perceptual processing for visual language (i.e., print) that would otherwise be degraded by visual eccentricity. However, there is no research to date that has investigated whether a similar effect is seen for other types of visual language, like sign language.

Peripheral Perception of ASL

There is scant research on peripheral sign identification in deaf signers. The research that does exist suggests, as expected, that deaf signers are able to identify signs in the periphery, but their ability to do so is negatively affected by increasing eccentricity from fixation both within the intermediate periphery (i.e., decreases from ~95% at 14.4° to ~68% at 45°; Emmorey, Bosworth, et al., 2009) and within the extreme periphery (i.e., decreases from ~80% at 45°- 61° to ~68% at 61°- 77°; Swisher et al., 1989). Swisher et al. (1989) used naturally produced signs that contained motion and it is therefore unclear whether discrimination ability was distinct from the enhanced motion detection abilities described above (e.g., Dye & Bavelier, 2013; Pavani & Bottari, 2012). Although Emmorey, Bosworth et al. (2009) used static images, the stimuli were presented at eccentricities beyond those experienced during natural sign comprehension (i.e., generally less than 30°; Bosworth et al., 2019) and therefore the effect of eccentricity may be an overestimate of what would be observed for moderate eccentricities within the field of view of natural sign comprehension. Importantly, no prior studies have investigated whether lexical properties of the stimuli have an impact on peripheral processing abilities. Although Swisher et al. (1989); Emmorey, Bosworth, et al. (2009), and Bosworth et al. (2019) all used semantically meaningful stimuli, they did not compare them to perceptually valid but semantically nonmeaningful stimuli and therefore the contribution of knowledge of a visual language is less clear.

The Current Study

In Experiment 1 we assessed the effect of eccentricity on ASL handshape identification by comparing deaf signers' ability to identify handshapes from ASL fingerspelling signs when they are presented at moderate eccentricities within briefly flashed static images that do not contain any component of motion. In Experiments 2 and 3, we assessed deaf signers' abilities to identify or discriminate handshapes in dynamically moving stimuli that varied in linguistic meaningfulness to directly examine the contribution of sign language knowledge. Because none of the prior studies on ASL perception compared discrimination ability between deaf signers and hearing individuals (either signers or nonsigners), we compared deaf signers' performance to the performance of hearing people who know at least a minimum amount of sign language to identify handshapes (Experiment 1) or have no knowledge of ASL (Experiments 2 & 3). We also tested deaf signers with a range of ages of initial sign acquisition to parallel the range in signing experiences among the population of deaf ASL signers.

If sign language plays a role in visual processing enhancements, deaf signers should be better able to peripherally identify visual forms within meaningful stimuli (i.e., signs) than within stimuli with similar perceptual qualities that cannot be mapped to meaning (e.g., pseudosigns). Such an enhancement for signs over pseudosigns (i.e., a *sign superiority effect*) would be analogous to the word superiority effect for print (Cattell, 1886; Reicher, 1969; Wheeler, 1970), as demonstrated by hearing individuals. Furthermore, if the decrease in visual perception in the far compared to the near periphery (i.e., the eccentricity effect) is smaller for signs than for pseudosigns for deaf signers, this would suggest that a visual language has an impact on visual processing pathways (e.g., the ventral stream responsible for identification). In the current study we assess whether the ability to discriminate handshape is enhanced, and the eccentricity effect is decreased, when the stimulus is part of a meaningful linguistic sign relative to a meaningless stimulus. If so, this would imply that sign language experience contributes to deaf signers' enhanced peripheral perception.

We hypothesized that deaf signers would identify handshapes more accurately, and with *smaller* effects of eccentricity, than hearing individuals based on past research demonstrating peripheral perceptual enhancements for deaf signers (Dye & Bavelier, 2013). We also hypothesized different patterns of interactions between participant group and eccentricity for different types of stimuli depending on the source of these perceptual enhancements. If deaf signers' peripheral processing enhancements are due to enhancements for processing motion, there should be an interaction between participant group and eccentricity only for stimuli that contain motion (i.e., in Experiments 2 and 3) but not for static images (i.e., in Experiment 1). If deaf signers' peripheral processing enhancements are driven by experience with a signed language, then in Experiments 2 and 3 there should be interactions between participant group, eccentricity, and lexical status. Specifically, the effects of eccentricity should be smaller for linguistically meaningful stimuli (e.g., ASL signs or fingerspelled words) than for meaningless stimuli (e.g., pseudosigns or fingerspelled nonword sequences) among the group of deaf signers, but this interaction should not be apparent for hearing nonsigners.

Experiment 1: Static Fingerspelling Handshapes

The first question we addressed is whether deaf signers are able to identify briefly flashed static images of ASL fingerspelling handshapes in the periphery. Static handshapes are more meaningful than dots or oriented lines, as have been used in previous experiments, but contain no semantic information nor any movement (as we controlled for by excluding the letters J and Z). We predicted that signers would successfully identify handshapes but would be more accurate in the near versus far periphery. Critically, we sought to address whether the negative effect of eccentricity on identification ability was reduced for deaf signers relative to hearing L2 learners of ASL. If deafness is responsible for the reorganization of visual processing systems associated with visual form discrimination (i.e., in addition to motion processing) then deaf signers should show reduced eccentricity effects compared to hearing signers with less signing experience. Hearing signers are a necessary comparison case for this study because they must at least know the ASL alphabet in order to perform a free-response identification task. Furthermore, hearing signers represent a larger variability in signing ability and experience, and therefore allow us to investigate whether sign language proficiency interacts with eccentricity effects separately from deafness.

Method

This study was approved under University of South Florida IRB Pro00030842, Visual Perception and ASL. We calculated the power needed to detect the critical two-way interaction between eccentricity and hearing status using the PANGEA program (Westfall, 2016). With 24 items per condition and at least 40 participants per group, we have power = 0.91 to detect an interaction with a moderate effect size of $d = 0.28$.

Participants. One hundred thirteen participants (57 deaf; 56 hearing) were recruited and compensated with course credit or monetary compensation in accordance with IRB protocol. Deaf participants were recruited through community outreach in three major metropolitan areas, one in the Northeast, one in the mid-Atlantic, and one in the Southeastern United States, through emails to community groups, word of mouth, social media advertising, and at a conference booth. Inclusion criteria required that participants were born profoundly deaf or became deaf before the age of three and use ASL as their primary means of communication. Hearing participants were recruited from the Psychology department subject pool at a university in the Southeastern United States, as well as with fliers distributed throughout the surrounding community, including students enrolled in ASL/interpreting classes. They had to have taken at least one class of ASL and know the ASL fingerspelling alphabet.

Ninety-eight participants (47 deaf and 51 hearing) were included in the analyses reported below.[1] Of the included deaf participants, 41 were born profoundly deaf and six became deaf before age three. Of the included deaf participants, 25 were first exposed to ASL at birth and 20 were exposed to ASL between the age of one and 35 (two deaf participants declined to state their age of first exposure) so that their average year of first exposure was 5.3 years of age (*SD* = 9.0) and their average number of years using ASL was 27 (*SD* = 13.2). The included hearing participants, on average, were first exposed to ASL around 15.2 years of age

Figure 1. Example stimuli for the letter "D" in each of the four conditions in Experiment 1. The model in the bottom panels gave signed consent for his likeness to be published in this article. The face of the model in the top panels is blurred because she could not be contacted for publication permissions, but her face was not blurred in the images used in the experiment. See the online article for the color version of this figure.

(*SD* = 6.3) and their average number of years using ASL was 4.8 (*SD* = 3.9).

Apparatus. Eye movements were recorded with an SR Research Ltd. Eyelink 1000plus eye tracker (sampling rate of 500 Hz) in remote setup. Participants wore a sticker on their foreheads that measured and corrected for head movements. Viewing was binocular, but only movement of the right eye was recorded. Participants were tested at three study sites: at site 1, viewing distance was 60 cm from a 1024 × 768 monitor (refresh rate = 150 Hz), and at sites 2 and 3 viewing distance was 55 cm from a 1280 × 1024 monitor (refresh rate = 60 Hz). Stimuli were scaled so that the images subtended the same degree of visual angle (°) in both setups.

Materials and design. Stimuli consisted of 96 static images of one of two models producing an ASL handshape (i.e., one of the letters of the English alphabet) with the right hand (Model 1) or left hand (Model 2). In the near eccentricity, the handshape was formed next to the model's face; in the far eccentricity it was formed along the same horizontal plane but with the elbow at a right angle (see Figure 1). Although the productions differed slightly from conventional fingerspelling locations, native signers were easily able to identify them. Each of the 24 letters (i.e., excluding J and Z, which involve motion) was presented in each condition of a 2 (eccentricity: near ~ 6° vs. far ~ 15°) × 2 (visual field: left vs. right) repeated measures design.

Procedure. Participants provided informed consent in written English; they were given the opportunity to ask questions and receive clarification about the document in ASL. They answered a brief series of demographic questions in written English or ASL. Hearing participants also completed an ASL receptive skills quiz to measure proficiency. The quiz contained 11 short videos of signers spelling words in isolation ($n = 6$), telling stories (e.g., a monologue; $n = 3$) or having a conversation (e.g., a dialogue; $n =$

[1] Four deaf participants were excluded due to a failure to calibrate the eye tracker or experimental errors, and 6 were excluded for excessive data loss (i.e., more than 42% of trials lost in at least one condition). Three hearing participants were excluded for excessive data loss, 1 was excluded for not knowing ASL, and 1 was excluded for having amblyopia.

2). Participants answered multiple-choice questions in which they identified a fingerspelled word ($n = 8$) or answered a comprehension question ($n = 6$). The videos, which varied in difficulty, were taken from published curriculum materials from ASL courses at the university where the hearing participants were recruited (Smith & Surrency, 2014a, 2014b; Surrency & Smith, 2016a, 2016b). Hearing participants' mean score was 79.6% correct ($SD = 16.69$), suggesting they had basic knowledge of ASL signs, but there was also enough variability to investigate the relationship between ASL knowledge and performance on the experimental task.

For the experiment, participants were seated in front of an eye-tracking camera and a monitor that presented the stimuli via Experiment Builder software (SR-Research Ltd., Ontario, Canada). Instructions were presented to hearing participants in English and to deaf participants in ASL. Prior to the experiment, a 5-point calibration and validation sequence was conducted (error remained below 0.5°). Trials started with a fixation point in the location where the signer's face would appear. Once the experimenter started the trial, the fixation point was replaced by the image of the signer. Participants were to identify the letter handshape without moving their eyes from the location of the signer's face. Each image flashed for 400ms. If a participant moved the focus of their eye outside of a 60 pixel ellipse (~2°) around the main fixation point for 50ms or more, this resulted in visual feedback (i.e., a red screen) and exclusion of the trial. This ensured that the images were only perceived in the eccentricity determined by the experimental condition. There were four practice trials. The 96 experimental trials were pseudorandomized across four conditions such that the same letter was not presented immediately in succession.

Results

1863 trials were removed (20%) due to track loss (17% and 23% in the far and near eccentricity, respectively).[2] All analyses were conducted in R (Version 3.6.1; R Core Team, 2019). Trial-level accuracy (i.e., binary) data were fit using Generalized Linear Mixed Effect Regressions (GLMM) via the glmer() function from the lme4 package (Version 1.1–21; Bates, Mächler, Bolker, & Walker, 2015). To test if deaf signers showed enhanced peripheral processing relative to hearing signers, participant group, eccentricity, and their interaction were entered as predictors in the model. All predictors were entered with centered contrasts (i.e., eccentricity: far = −0.5, near = 0.5 and participant group: deaf = −0.5, hearing = 0.5, respectively) so the effect coefficients represent the main effects collapsed across the other factor. The random effects structure contained intercepts and slopes for eccentricity for both subjects and items. Visual field (left vs. right) did not significantly affect performance and is not included in the analyses presented below.

The analysis revealed a significant effect of participant group (deaf signers performed better than hearing signers; $b = -0.89534$, $z = -6.035$, $p < .001$), a significant effect of eccentricity (performance was better at the near eccentricity than at the far eccentricity; $b = 1.16731$, $z = 5.353$, $p < .001$), and no interaction ($b = 0.03325$, $z = 0.197$, $p = .84$; see Figure 2). Hearing signers showed an eccentricity effect that was similar to that of the deaf signers. Thus, although deafness did lead to an increase in accuracy overall, there was no evidence that deafness leads to an enhancement of peripheral visual form discrimination,

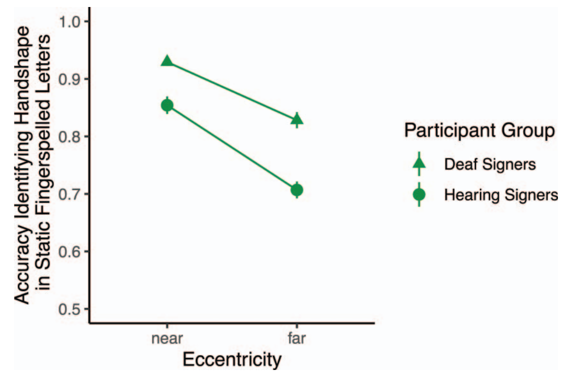

Figure 2. Effect of eccentricity on the accuracy of handshape identification by deaf and hearing signers for briefly flashed static images in Experiment 1. Error bars represent ±1 *SEM*. See the online article for the color version of this figure.

through the reduction of an eccentricity effect, in the absence of motion or high level linguistic meaningfulness.[3]

In order to examine the influence of sign language knowledge within a highly variable population, we also analyzed accuracy for the hearing participants only in a separate model. We included proficiency on the ASL quiz as a centered continuous predictor, eccentricity, and their interaction as fixed effects and random slopes for items, intercepts only for participants. In this analysis, higher proficiency was associated with higher accuracy ($b = 2.2440$, $z = 3.372$, $p < .001$), accuracy was better at the near than the far eccentricity ($b = 1.0943$, $z = 4.633$, $p < .001$), but again there was no interaction ($b = 0.8129$, $z = 1.008$, $p = .31$). Thus, at least for minimally meaningful motionless stimuli, sign language knowledge does not contribute to enhanced peripheral processing above and beyond overall accuracy.

Summary of Experiment 1

The results of Experiment 1 demonstrate that, as expected, deaf signers exhibit an eccentricity effect whereby their ability to identify an ASL fingerspelled letter is reduced at further eccentricities (see also Emmorey, Bosworth, et al., 2009; Swisher et al., 1989). Hearing signers (i.e., individuals who had learned at least some ASL as an L2) also showed an eccentricity effect, performed worse overall relative to deaf signers, and performed better with higher proficiency, but proficiency was not associated with decreased effects of eccentricity. Thus, for static ASL handshapes, deaf signers do not show peripheral identification enhancements relative to hearing signers, nor do more proficient hearing signers

[2] Data loss was due to participants moving their eyes outside of the gaze location, a small area of the signers' face. Individuals, whether deaf or hearing, signers or non-signers, are not used to holding fixation and attending to information, especially moving stimuli, in the periphery because they can usually move their eyes. This amount of data loss is not unusual in an eye tracking study, especially with such a strict fixation criterion.

[3] It could be argued that single handshapes are semantically meaningful because of their ability to depict categories of objects for some classifiers in ASL. Although we agree that some handshapes may carry more semantic value than individual English letters, static handshapes cannot convey meaning without at least minimal movement or placement in space.

show peripheral identification enhancements relative to less proficient hearing signers, above and beyond an overall accuracy advantage at both eccentricities. This supports the conclusion that deafness may impact the neural organization of dorsal stream processing for motion but not ventral stream processing for identification of static stimuli in the periphery (Neville & Lawson, 1987b; Pavani & Bottari, 2012). However, these images did not contain motion, and it is possible that isolated fingerspelling letters are not sufficiently meaningful to elicit perceptual enhancements that may be attributable to sign language knowledge.

Experiment 2: Fingerspelled Word and Nonword Sequences

In the second experiment, we address whether adding motion and using more semantically meaningful stimuli would reveal peripheral enhancements for deaf signers relative to hearing nonsigners. Experiment 1 lacked the component of motion that was present for the natural ASL signs (Swisher et al., 1989) and the dot stimuli used in prior experiments (see Dye & Bavelier, 2013). Thus, in Experiment 2, we presented fingerspelled letter sequences. Fingerspelled sequences incorporate motion, as signers make transitional movements between the signs that represent each letter handshape.[4]

In contrast to single letters, fingerspelled sequences can represent English words that carry semantic meaning. To assess the degree to which lexical information impacts peripheral processing enhancements, we compared letter sequences that correspond to an English word (e.g., f-u-n), and those that did not (e.g., n-u-f). Thus, analogous to the word superiority effect for print in hearing individuals (Cattell, 1886; Reicher, 1969; Wheeler, 1970), if deaf signers represent fingerspelled sequences as holistic representations (i.e., the English words they map onto) we would expect them to be more accurate in identifying the handshapes within a word than within a nonword.

In Experiment 2, we changed the task from a free response identification task to a two-alternative forced choice (2AFC) discrimination task so that we could compare deaf signers to hearing nonsigners to provide a stronger test of the effect of sign language knowledge. An important aspect of this experiment is the within-participant manipulation of the lexical status of the stimuli mentioned above. With this approach we can investigate the contribution of sign knowledge within the deaf signing subjects and compare their patterns of effect to a group who has no knowledge of the language. Lexicality should only have an effect if someone knows the language and if language knowledge has an impact on the eccentricity effect.

We predicted that deaf signers would show an effect of eccentricity for fingerspelled sequences (higher accuracy in the far presentation relative to the near), and that this effect might be reduced relative to the eccentricity effect in hearing nonsigners. We further predicted that there would be an interaction between stimulus type and eccentricity for deaf signers, whereby the deaf signers would show a smaller eccentricity effect for the words than nonwords. In contrast, for the hearing nonsigning participants, we predicted an effect of eccentricity, but no effect of lexical status (i.e., no difference between word and nonword sequences).

Method

This study was approved under University of South Florida IRB Pro00038132, Enhanced Peripheral Processing in Deaf Individuals. We calculated the power needed to detect the critical three-way interaction between eccentricity, condition, and hearing status using the PANGEA program (Westfall, 2016). With 35 items per condition and at least 40 participants per group, we have power = 0.97 to detect an interaction with a moderate effect size of d = 0.28.

Participants. One hundred fifteen participants (61 deaf; 54 hearing) were recruited. Twelve of the deaf participants had also been in Experiment 1. The inclusion criteria for the deaf participants were the same as in Experiment 1. The inclusion criterion for the hearing participants was to have no prior knowledge of ASL.

Ninety-one participants were included in the analyses reported below (42 deaf and 49 hearing).[5] Of the included deaf participants, 36 were born profoundly deaf and six became deaf between the age of two and 10. Of the included deaf participants, 23 were first exposed to ASL at birth and 17 were exposed to ASL between the years of 1 and 35 (two deaf participants declined to state their age of first exposure) so that their average year of first exposure was 5 years of age (SD = 9.0) and their average number of years using ASL was 21.6 (SD = 9.5).

Materials and design. Stimuli consisted of 35 three-letter items that were presented in two lexical status conditions (word[6] vs. nonword sequences) and at two eccentricities (near, ~ 6° vs. far, ~14°), constituting a 2 × 2 design. For each word, a nonword was created by reversing the order of the letter sequence (i.e., b-o-y became y-o-b). In the word condition, the nontarget letter, if inserted into the sequence, would make a real word (e.g., in the word sequence b-o-y, the two choices were "o" and "a", as the letter "a" would produce a real word b-a-y). In the nonword condition, the nontarget letter would produce a different nonword (e.g., in the sequence y-o-b, the nontarget option "a" would produce the nonword y-a-b). A strength of our design is that any idiosyncrasies of a given item could contribute only to item level error variance, but not to the fixed effects of interest because the same handshape options in the 2AFC task were used in all conditions and the same flanking letters were used for each condition of the stimulus (e.g., f-u-n and n-u-f at both the near and far eccentricities).

Stimuli were created by having a deaf native-signing model produce each letter sequence at each periphery; by the side of the face in the near periphery, and by extending her arm to the side in the far periphery (see Figure 3). Because Experiment 1 revealed no effect of left versus right visual field, they were all produced in the left visual field, which was natural for the sign language model. The signer model produced both words and nonwords. Stimuli were then edited such that the onset of the video corresponded with

[4] Fingerspelled sequences may introduce a potential "crowding" effect (Levi, 2008), however this would be realized as temporal crowding as opposed to spatial crowding as it is usually conceptualized.

[5] Twelve deaf participants were excluded for calibration or experimental program errors, one was excluded for having ASL as their 5th learned sign language, and six were excluded for excessive data loss (i.e., more than 68% missing in any condition). Five hearing participants were excluded for experimental program errors.

[6] For 21 of the stimuli, there is an ASL sign equivalent of the word.

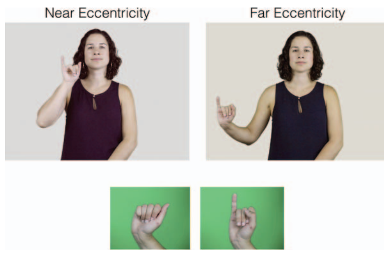

Figure 3. Example stills of the middle letter for the near (left panel) and far (right panel) conditions of the stimulus "bid" in Experiment 2. Two alternative forced choice options for the handshape, which were used in both conditions are presented below in the figure, but were presented after the video in the experiment. The model in this figure gave signed consent for her likeness to be published in this article. See the online article for the color version of this figure.

the signer having already formed the first handshape of the sequence (i.e., there was no transitional movement), and the offset of the video occurred shortly after the final handshape was formed completely. Videos were edited to be exactly 500ms long.

Procedure. The procedure was similar to Experiment 1 except that the stimuli were video clips rather than static images, and the participants were prompted after each trial to select the middle handshape from the sequence from two static images of handshapes. As in Experiment 1, trials started with a fixation point in the location where the signer's face would appear. Once the experimenter started the trial, the fixation point was replaced by the video of the signer. Participants were instructed to focus on the signer without moving their eyes from the location of the signer's face. If a participant moved the focus of their eye outside of a 60 pixel ellipse (~2°) around the main fixation point for 50ms or more, this resulted in visual feedback (i.e., a red screen) and exclusion of the trial. There were four practice trials. The 140 experimental trials were pseudorandomized so that the same item (consisting of both word and nonword versions of the pair) was not presented immediately in succession. Participants made their choice by pressing on one of two keys (one on the left and the other on the right) on a keyboard or response pad that corresponded to left and right choices. Participants rested a finger on each key, so they did not need to look down between trials.

Results

2117 trials (17%) were removed due to track loss (17%, 15%, 18%, and 17% in the far nonword, far word, near nonword, and near word conditions, respectively). The GLMM analysis consisted of fixed effects containing centered contrasts for participant group (deaf = −0.5, hearing = 0.5), eccentricity (far = −0.5, near = 0.5), and lexical status (nonword = −0.5, word = 0.5), and the interactions between each of these factors (see Table 1; Figure 4). The random effects consisted of intercepts and slopes for all of the fixed effects for items and intercepts and slopes for lexical status and its interaction with eccentricity for subjects.

The analysis revealed a significant main effect of participant group in which hearing nonsigners were less accurate than deaf signers ($p < .001$), and a significant main effect of eccentricity in which accuracy was higher in the near condition than in the far condition ($p < .001$). There was no main effect of lexical status; on average accuracy was similar for words and nonwords ($p = .57$). There was a marginally significant interaction between-participants group and eccentricity in which the effect of eccentricity was larger for hearing nonsigners ($p = .06$). There was a significant interaction between participant group and lexical status ($p < .05$), but a follow up analysis revealed that the effect of lexical status was not significant for either group individually (see below). There was no interaction between eccentricity and lexical status such that the effect of lexical status was similar at the near and far eccentricities ($p = .34$). Lastly, there was no three-way interaction, suggesting that the patterns of interactions between eccentricity and lexical status were similar for the two groups ($p = .90$).

Based on the significant interaction between participant group and lexical status, we conducted separate analyses for each group. Contrary to our expectations, neither group's effect of lexical status, nor the interactions between lexical status and eccentricity were significant (all $ps > .12$), but both group's effects of eccentricity were significant (both $ps < .05$). Thus, the significant interaction between lexical status and participant group in the main analysis is likely a statistical anomaly in which two nonsignificant effects in opposite directions can lead to a significant interaction.

Summary of Experiment 2

The results of Experiment 2 show that, as expected, deaf signers exhibit an eccentricity effect when discriminating handshapes in fingerspelled sequences. However, contrary to our hypothesis, they did not show an effect of lexical status. This finding may suggest that deaf signers do not activate word knowledge when processing fingerspelled letter sequences. More likely, deaf signers may have activated word knowledge but either the timing of word recogni-

Table 1
Results of the Linear Mixed Effects Model for Handshape Discrimination Accuracy in Experiment 2

Effect	Estimate	*SE*	|z|	*p* value
Intercept	1.81212	0.12123	14.948	$<.001^{***}$
Participant group	−2.07761	0.22644	9.175	$<.001^{***}$
Eccentricity	0.41413	0.11570	3.579	$<.001^{***}$
Lexical status	0.05526	0.09781	0.565	.57
Participant Group × Eccentricity	−0.32768	0.17663	1.855	$.06^{\dagger}$
Participant Group × Lexical Status	−0.39692	0.17305	2.294	$.02^{*}$
Eccentricity × Lexical Status	0.16891	0.17882	0.945	.34
Participant Group × Eccentricity × Lexical Status	0.04035	0.33047	0.122	.90

$^{\dagger}p < .10$. $^{*}p < .05$. $^{***}p < .001$.

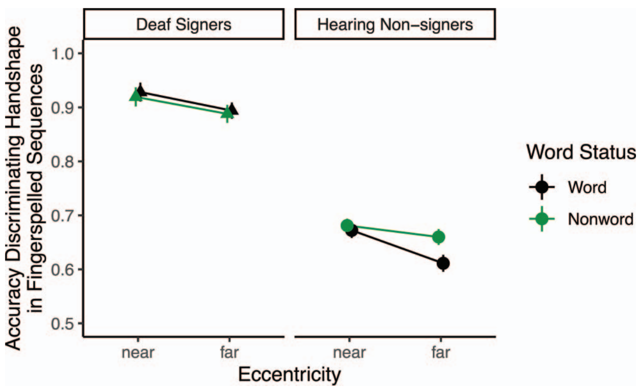

Figure 4. Condition means for handshape discrimination accuracy in Experiment 2. Error bars represent ±1 *SEM*. See the online article for the color version of this figure.

tion or the specific processing demands did not translate to differences in performance on this task.

The deaf signers were overall more accurate than hearing nonsigners, as expected, and showed numerically smaller effects of eccentricity (although this interaction was marginally significant), providing some evidence that motion may be sufficient to produce perceptual enhancements for stimulus identification/discrimination for deaf signers.

Experiment 3: ASL Lexical Signs and Pseudosigns

In Experiment 3, we investigated whether presenting ASL signs and pseudosigns in near and far eccentricities would bring about a linguistically mediated peripheral enhancement for deaf signers. In both prior experiments, the mapping from perceptual representations to meaning was minimal, arbitrary, and for the most part mediated through English orthography. Experiment 2 demonstrated that visual motion did lead to peripheral identification enhancements for deaf signers, but the amount of semantic information in fingerspelled word versus nonword sequences was not sufficient to reveal a fingerspelling-based word superiority effect. Therefore, in Experiment 3 we used stimuli that are fully formed meaningful signs in ASL, the primary language of the participants. We predicted that deaf signers would perform better in the near than in the far eccentricity as was demonstrated in Experiments 1 and 2. We further predicted that accuracy would be better for signs than pseudosigns, providing evidence for a sign superiority effect. We also predicted that there would be an interaction, such that the effect of lexical status (sign vs. pseudosign) would be most evident in the far eccentricity. Finally, if sign language experience is responsible for the reorganization of visual processing systems, beyond the effects of motion, we hypothesized that deaf signers would show a smaller effect of eccentricity than hearing nonsigners, and that this reduction in the eccentricity effect would be most notable for signs than pseudosigns.

Method

This study was approved under University of South Florida IRB Pro00038132, Enhanced Peripheral Processing in Deaf Individuals. We calculated the power needed to detect the critical three-way interaction between eccentricity, condition, and hearing status using the PANGEA program (Westfall, 2016). With 40 items per condition and at least 40 participants per group, we have power = 0.98 to detect an interaction with a moderate effect size of d = 0.28.

Participants. One hundred fifteen participants (61 deaf; 54 hearing) were run in the experiment. The same participants were recruited for Experiment 3 as for Experiment 2. Most participants completed both experiments in one session, but a subset were included in only one of the two experiments, either because of equipment failure in one experiment, or because they exceeded the data loss threshold in one experiment but not the other.

Ninety-eight participants (49 deaf and 49 hearing) were included in the analyses reported below.[7] Of the included deaf participants, 43 were born profoundly deaf and six became deaf between the age of 1 and 10. Of the included deaf participants, 29 were exposed to ASL at birth and 17 learned ASL by, on average, age 13 (range 1–35 years old; three participants did not provide information about their age of acquisition of ASL) so that their average age of first exposure was 4.8 years (SD = 8.6) and their average number of years using ASL was 22.8 (SD = 9.5).

Materials and design. Stimuli consisted of 40 stimulus pairs presented in two lexical status conditions (sign vs. pseudosign) and at two eccentricities (near, ~ 8° vs. far, ~12°), constituting a 2 × 2 design. For each sign, a pseudosign was created by maintaining the handshape, but changing one or two of the other sign parameters (e.g., movement, secondary location, or orientation) to make a nonsense but phonologically possible sign. Stimuli were selected so that, in the sign condition, another handshape could be presented that would make a real sign and in the pseudosign condition the same handshape would produce a pseudosign. Although some signs contained sign-internal movement, this was consistent across eccentricity conditions for the same item as well as between the sign and pseudosign versions of the items and therefore should not change the effects of condition investigated here.

Stimuli were created by having a deaf native-signing model produce each sign and pseudosign at each periphery; the signs in the near periphery were produced by the side of the face, and the signs in the far periphery were produced in more neutral space below and to the left of the signer's face (see Figure 5). Stimuli were edited such that the onset of the video was six frames before the handshape was deemed fully formed by a native signer, and the offset of the video occurred six frames after the sign ended and the hand was beginning to transitionally move back to resting position. Videos varied in length (M = 855 ms, range: 366–1433 ms), but within a pair, at the far eccentricity they did not significantly differ (i.e., the mean difference was 48 ms longer in the sign version; $t(39) = 1.35$, $p = .18$), and at the far eccentricity they differed slightly (i.e., the mean difference was 77 ms longer in the pseudosign version; $t(39) = 2.20$, $p < .05$).

Procedure. The procedure was similar to Experiment 2 in that the stimuli were videos and the participants were prompted after each trial to select the handshape from two static images.

[7] Four deaf participants were excluded for calibration or experimental program errors, one was excluded for having ASL as the 5th learned sign language, and seven were excluded for excessive data loss (i.e., more than 68% missing in any condition). Five hearing participants were excluded for calibration or experimental program errors.

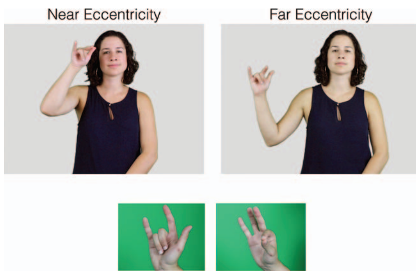

Figure 5. Example stills for the near (left panel) and far (right panel) conditions of the stimulus "airplane" in Experiment 3. Two alternative forced choice options for the handshape, which were used in both conditions are presented below in the figure, but were presented after the video in the experiment. The model in this figure gave signed consent for her likeness to be published in this article. See the online article for the color version of this figure.

As in Experiment 2, trials started with a fixation point in the location where the signer's face would appear. Once the experimenter started the trial, the fixation point was replaced by the video of the signer. Participants were instructed to focus on the signer without moving their eyes from the location of the signer's face. If a participant moved the focus of their eye outside of a 60 pixel ellipse (~2°) around the main fixation point for 50ms or more, this resulted in visual feedback (i.e., a red screen) and exclusion of the trial. There were four practice trials. The 160 experimental trials were pseudorandomized so that the same item (consisting of both sign and pseudosign versions of the pair) was not presented immediately in succession. Participants made their choice by pressing on one of two keys (one of the left and the other on the right) on a keyboard or response pad that corresponded to left and right choices. Participants rested a finger on each key so they did not need to look down between trials.

Results

3800 trials (24%) were removed due to track loss (20%, 26%, 25%, and 27% in the far pseudosign, far sign, near pseudosign, and near sign conditions, respectively). Data were analyzed with a GLMM with the same fixed effects structure as Experiment 2 and can be interpreted analogously (see Table 2; Figure 6). The random effects structure contained the maximal random effects for items and intercepts only for participants.

The analysis revealed a significant main effect of participant group in which hearing nonsigners were less accurate than deaf signers ($p < .001$), as expected. There was also a significant main effect of eccentricity, in which accuracy was higher in the near condition than in the far condition ($p < .005$), and a significant main effect of lexical status in which accuracy was higher for signs than pseudosigns (i.e., a sign superiority effect; $p < .005$). There was no interaction between eccentricity and participant group ($p = .44$) or between eccentricity and lexical status ($p = .10$). There were only marginally significant interactions between participant group and lexical status (i.e., there was a numerically larger effect of lexical status for the hearing nonsigners; $p = .09$) and a marginal three way interaction between participant group, eccentricity, and lexical status ($p = .08$). This latter finding, although marginal, is suggestive that the way in which lexical status impacted the eccentricity effect differed between the two groups (see below).

To better understand these complicated patterns, we ran analyses for each of the participant groups separately, with eccentricity, lexical status, and their interaction as fixed effects. The random effects structure for the model on the deaf signers contained the maximal random effects for items and intercepts and the slope for eccentricity and its interaction with lexical status for participants. The random effects structure for the model on the hearing nonsigners contained the maximal random effects for items and intercepts only for participants.

The analysis of the deaf signers revealed a marginally significant effect of eccentricity in which they were more accurate at the near eccentricity ($p = .09$). As predicted, there was a significant effect of lexical status in which they were more accurate for signs than pseudosigns ($p < .005$), thereby showing a clear sign superiority effect. Most importantly, there was also a marginally significant interaction between lexical status and eccentricity, in which the effect of eccentricity was weaker for the signs than for the pseudosigns ($p = .07$; Table 3). Follow-up GLMM analyses that tested the effect of eccentricity run separately for the two lexical status conditions revealed that the deaf signers showed a significant effect of eccentricity for pseudosigns ($b = 1.1854$, $z = 3.29$, $p = .001$) but not for signs ($b = 0.05221$, $z = 0.09$, $p = .93$). This pattern of data suggests that the lexical status of a meaningful ASL sign may spare deaf signers from the perceptual degradation

Table 2
Results of the Linear Mixed Effects Model for Handshape Discrimination Accuracy in Experiment 3

Effect	Estimate	*SE*	|z|	*p* value
Intercept	3.0688	0.2317	13.25	$<.001^{***}$
Participant group	−1.8962	0.2078	9.123	$<.001^{***}$
Eccentricity	0.4876	0.1603	3.043	$<.005^{**}$
Lexical status	0.7716	0.2634	2.929	$<.005^{**}$
Participant Group × Eccentricity	−0.2128	0.2764	0.770	.44
Participant Group × Lexical Status	−0.6200	0.3644	1.701	$.09^{\dagger}$
Eccentricity × Lexical Status	−0.6102	0.3761	1.622	.10
Participant Group × Eccentricity × Lexical Status	1.0219	0.5769	1.771	$.08^{\dagger}$

$^{\dagger} p < .10$. $^{**} p < .005$. $^{***} p < .001$.

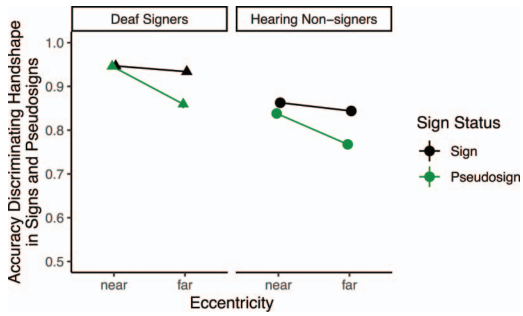

Figure 6. Condition means for handshape discrimination accuracy in Experiment 3. Error bars represent ±1 *SEM*. See the online article for the color version of this figure.

associated with presenting visual stimuli at a far eccentricity, which is likely a result of extensive experience with sign language.[8]

For the hearing nonsigners, there was a significant effect of eccentricity in which they were more accurate at the near eccentricity ($p < .005$), as expected. There was an unexpected marginally significant effect of lexical status in which they were more accurate for the signs than the pseudosigns ($p = .06$). However, importantly, there was no interaction between lexical status and eccentricity; the effect of eccentricity was similar for signs and pseudosigns ($p = .95$; Table 4). Follow-up GLMM analyses that tested the effect of eccentricity run separately for the two lexical status conditions revealed that the hearing nonsigners showed a significant effect of eccentricity for pseudosigns ($b = 0.4555$, $z = 2.448$, $p = .01$) and a marginally significant effect for signs ($b = 0.3809$, $z = 1.871$, $p = .06$). This pattern of data suggests that, although lexical status in an unknown language does contribute to better perceptual discrimination (possibly due to phonotactic features of ASL; see summary below), it does not have the same mitigating effect on the perceptual degradation associated with eccentricity as it does for deaf signers with knowledge of the language.

Lastly, we visualized the model estimates of effect size and variability for the effects of lexical status, eccentricity, and their interaction from the separate models for the deaf signers and hearing nonsigners using the sjplot() package in R (see Figure 7). The model effect estimates are represented as odds ratios, the exponent of the log-odds coefficients from the GLMM models. An odds ratio of 1 indicates a null effect of the fixed effect of interest (i.e., conditions in which the participant is equally likely to be accurate as to be inaccurate) and odds ratios further away from 1 represent effect sizes that are larger, with those below 1 representing that accuracy decreases and those above 1 representing that accuracy increases. This makes the pattern of results reported above quite clear. For both groups, there is an effect of lexical status (i.e., higher accuracy for signs than pseudosigns), which is stronger for deaf signers, indicated by the estimate being further from 1. There is also an effect of eccentricity (i.e., higher accuracy in the near than the far eccentricity), which is stronger for the hearing nonsigners, indicated by smaller variability around the estimate. Most importantly, the estimate for the interaction (i.e., a smaller eccentricity effect for signs than pseudosigns) is much larger for the deaf signers than the hearing nonsigners, for whom the odds ratio for the interaction is essentially 1. Thus, although these interactions are marginally significant, when considering the effect size it seems as if there is a larger dependency of the eccentricity effect on lexical status for the deaf signers than there is for the hearing nonsigners (see effect sizes from the GLMM analyses above).

Table 3
Results of the Linear Mixed Effects Model for Handshape Discrimination Accuracy for Deaf Signers in Experiment 3

Effect	Estimate	*SE*	|z|	*p* value
Intercept	4.1873	0.3440	12.172	$<.001^{***}$
Eccentricity	0.6131	0.3583	1.711	$.09^{\dagger}$
Lexical status	1.3411	0.4640	2.890	$<.005^{**}$
Eccentricity × Lexical Status	−1.4017	0.7753	1.808	$.07^{\dagger}$

$^{\dagger}p < .10$. $^{**}p < .005$. $^{***}p < .001$.

Table 4
Results of the Linear Mixed Effects Model for Handshape Discrimination Accuracy for Hearing Nonsigners in Experiment 3

Effect	Estimate	*SE*	|z|	*p* value
Intercept	2.15076	0.19692	10.922	$<.001^{***}$
Eccentricity	0.41032	0.14201	2.889	$<.005^{**}$
Lexical status	0.48137	0.26010	1.851	$.06^{\dagger}$
Eccentricity × Lexical Status	−0.01717	0.25953	0.066	.95

$^{\dagger}p < .10$. $^{**}p < .005$. $^{***}p < .001$.

Summary of Experiment 3

The results of Experiment 3 show that, as expected, deaf signers exhibit an eccentricity effect when discriminating handshapes within ASL signs and phonologically plausible pseudosigns. In addition, linguistic meaningfulness (i.e., lexical status) impacted deaf signers' ability to process visual stimuli from their primary language, providing evidence for a sign superiority effect. Furthermore, lexical status appears to moderate the effect of eccentricity for deaf signers, although statistically the interaction between eccentricity and lexical status was only marginally significant. Although the deaf signers were extremely accurate at perceiving handshapes in known ASL signs, regardless of eccentricity; only their performance for pseudosigns depended on eccentricity (i.e., was significantly lower in the far periphery). This suggests that knowledge of, and experience with, a visual language may bring

[8] We also examined whether age of acquisition (AoA) of sign language affected the patterns of results with respect to eccentricity and lexical status by including age of acquisition and its interaction with the other variable as predictors in a GLMM. Although all the originally reported effects remain significant (eccentricity: $b = 0.732212$, $z = 4.986$, $p < .001$; lexical status: $b = 0.693125$, $z = 4.710$, $p < .001$; eccentricity by lexical status interaction: $b = -1.24899$, $z = -4.264$, $p < .001$), AoA did not affect overall accuracy ($b = 0.002330$, $z = 0.265$, $p = .79$) nor did it interact with eccentricity ($b = 0.005599$, $z = 0.378$, $p = .71$), nor sign status ($b = 0.008528$, $z = 0.576$, $p = .57$), nor was there a three-way interaction ($b = -0.010493$, $z = -0.354$, $p = .72$).

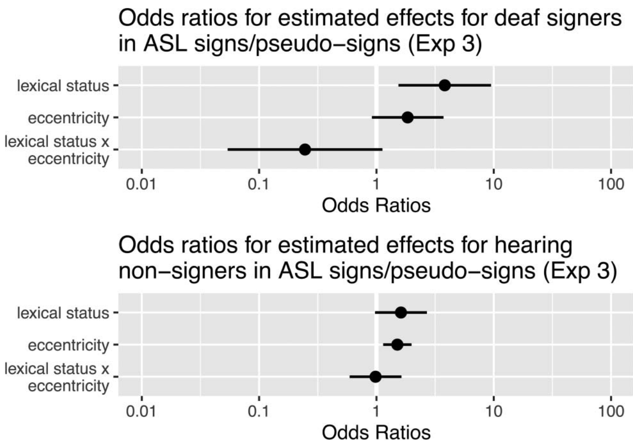

Figure 7. GLMM model estimates for the effect of lexical status, eccentricity, and their interaction in the analyses for deaf signers and hearing nonsigners in Experiment 3. ASL = American Sign Language.

about changes to visual processing systems that enhance peripheral discrimination abilities for visual forms.

The hearing nonsigners were less accurate than deaf signers, as expected. Surprisingly, they were also numerically better at detecting handshapes in signs versus pseudosigns, despite having no knowledge of ASL, but they were less sensitive to lexical status than the deaf signers (although this interaction was marginally significant). This effect may be explained by low-level perceptual properties of the videos, as was likely the case for the reversed effect of lexical status exhibited by hearing nonsigners in Experiment 2. Importantly, hearing nonsigners did not show the elimination of the eccentricity effect for ASL signs that deaf signers did.

General Discussion

We sought to understand how linguistic meaningfulness and motion contribute to peripheral processing advantages for deaf signers. We conducted a series of experiments with stimuli that did or did not contain motion and contained increasing amounts of linguistic content. Across our three experiments we found evidence that deaf signers are able to identify and discriminate visual forms (i.e., ASL handshapes) in peripheral vision more accurately than both hearing signers and hearing nonsigners, as predicted. In addition, both deaf signers and hearing individuals showed eccentricity effects, in which their identification and discrimination accuracy was worse at further eccentricities. When the stimuli contained motion (i.e., in Experiments 2 & 3), deaf signers did exhibit some decreased eccentricity effects relative to hearing nonsigners, suggesting that motion may be a necessary feature of visual stimuli for deaf individuals to demonstrate peripheral processing enhancements. Notably, we found that the ability to identify and discriminate visual forms (i.e., handshape) seems to represent processing advantages for deaf signers that go beyond those exhibited for motion. Specifically, as we predicted, deaf signers exhibited a sign superiority effect in Experiment 3, whereby the effect of eccentricity was not present for ASL signs in the same way that it was for pseudosigns, providing evidence for a sign superiority effect in ASL that mitigated the effect of eccentricity. Interestingly, they did not exhibit this effect of lexical status for fingerspelled word versus nonword sequences in Experiment 2, suggesting that fingerspelled sequences and signs may be subject to different processing constraints. We discuss each of these findings below.

Contributions of Language and Meaning to Peripheral Processing

Many peripheral processing enhancements for deaf signers have been attributed to reorganization of dorsal motion processing pathways in response to deafness (see Dye & Bavelier, 2013; Neville & Lawson, 1987b; Pavani & Bottari, 2012 for reviews). These studies have generally consisted of deaf individuals of a heterogeneous makeup in terms of their sign experience who were compared to hearing individuals who generally do not know sign language. These past studies did not use linguistically meaningful stimuli, so it is unclear how linguistic meaningfulness of the visual stimuli contribute to these enhancements. In our experiments, stimuli that contained motion led to a decrease in eccentricity effects for deaf signers relative to static stimuli. This finding suggests that deafness may contribute to the reorganization of dorsal visual processing systems that produce peripheral perceptual enhancements. This is parallel to processing enhancements deaf individuals have been shown to demonstrate for moving dots (Dye & Bavelier, 2013; Pavani & Bottari, 2012). However, the fact that deaf signers show a decrease in eccentricity effects for linguistically meaningful stimuli compared to meaningless stimuli suggests that experience with a visual language, in addition to deafness, may also contribute to the reorganization of visual processing systems that produce peripheral perceptual enhancements for deaf signers.

Our finding that deaf signers exhibit a sign superiority effect adds to a wealth of literature on the word superiority effect in print, which suggests that language knowledge facilitates lower level perceptual processing (Cattell, 1886; Reicher, 1969; Wheeler, 1970) and mitigates the perceptual degradation associated with presenting visual stimuli in peripheral vision (Bouma, 1973; Jordan et al., 2003). Although this interaction did not reach statistical significance at the .05 level, the estimated effect size was large especially in light of the almost-zero effect size for hearing nonsigning participants. We observed this effect for sign stimuli but not for fingerspelled sequences. The latter finding could be because the words in our stimuli were all very simple (e.g., boy, try). Further, in naturalistic signing these words have highly frequent lexical signs, and thus would rarely, if ever, be fingerspelled. Thus they may not have been automatically processed as their referent signs. Although there is ample evidence that deaf signers activate ASL during English semantic judgments (Morford, Wilkinson, Villwock, Piñar, & Kroll, 2011; Morford, Kroll, Piñar, & Wilkinson, 2014; Morford, Occhino-Kehoe, Piñar, Wilkinson, & Kroll, 2017), evidence that cross-linguistic activation is bidirectional is more variable. For example, there is evidence in ERP measures but not behavioral measures, and the effect seems to be dependent on language proficiency and dominance as well as by asymmetric reliance on orthographic versus phonological representations (Lee, Meade, Midgley, Holcomb, & Emmorey, 2019).

Although our study is the first to demonstrate the sign superiority effect, it is not the first to demonstrate enhanced perception by deaf signers in peripheral vision for simple stimuli like oriented lines (e.g., Stoll & Dye, 2019) or for linguistic information in general. For example, the fact that skilled deaf readers demonstrate an enhanced perceptual span relative to hearing readers of an equivalent grade level (Bélanger et al., 2012; Bélanger et al., 2018) also suggests that deaf signers recruit linguistic information to facilitate peripheral perception of visual forms. Future research should determine whether the sign superiority effect in peripheral vision exhibited by deaf signers is related to the enhanced perceptual span that some deaf readers demonstrate while reading English text.

Mechanisms of Perceptual Processing in Deaf Signers and Hearing Nonsigners

There were some surprising findings with regard to performance by the hearing nonsigners who we tested as a comparison group. In Experiment 2, there was no fingerspelled word superiority effect for hearing non-signers (as expected), yet there was a reversed superiority effect whereby hearing nonsigners were *less* accurate for the word than the nonword condition. We suggest this may be due to perceptual aspects of the stimuli. For example, the sign model may have produced the words more fluently and with more elision than the nonwords; the transitions between handshapes would have made the target handshape harder to perceive.[9] The deaf signers did not exhibit this reversed effect, suggesting they were less susceptible to perceptual aspects of the stimuli, or may have recruited lexical knowledge to compensate for them. Even if deaf signers did recruit lexical knowledge to compensate for the perceptual differences between the stimuli, they did not show a fingerspelled word superiority effect suggesting that, for these stimuli, the effects of lexical status are not very strong.

Similarly, in Experiment 3, we did not expect hearing nonsigners to show a sign superiority effect (e.g., the main effect of lexical status). It is possible that the effect for this group was also due to perceptual aspects of the stimuli, such as increased sonority of the sign stimuli relative to the pseudosign stimuli. For example, there may be a reason why the sign stimuli are attested in ASL; the pseudosigns were selected because they maintained the same handshape but, when combined with the other sign parameters, were unattested in ASL. The pseudosigns may be unattested because they are inherently harder to perceive and therefore less valuable for linguistic communication. Thus it is possible that the sign superiority effect observed among deaf signers was driven by cognitive mechanisms, whereas the effect observed among hearing nonsigners was driven by lower-level perceptual features. Importantly however, the two groups demonstrated different interactions between eccentricity and lexical status in Experiment 3. Namely, the deaf signers only showed an eccentricity effect for pseudosigns but not for signs, whereas the hearing nonsigners showed an eccentricity effect for both types of stimuli, suggesting that deaf signers may use lexical information to mitigate the effect of eccentricity in a way that hearing nonsigners are not able to. The interaction between participant group, eccentricity, and lexical status in Experiment 3 was only marginally significant, likely because the deaf signers were often at ceiling, which may have reduced the magnitude of the sign superiority effect in the aggregate data.

Limitations and Directions for Future Research

Although our manipulations of lexical status in Experiments 2 and 3 provide within-subjects information about the role of sign language, one could argue that the strongest test would be a between-participants comparison of deaf signers and deaf nonsigners. Indeed, this would round out our knowledge of variability across the entire population, but it would be difficult to identify a sufficient number of profoundly deaf individuals who have absolutely no knowledge of ASL. In addition, it could be argued that the strongest test of the pure effect of motion would be to compare stimuli that do or do not contain motion but are otherwise identical (e.g., moving vs. static single letters). However, such a comparison would not be able to assess the contribution of linguistic meaning that is the focus of our Experiments 2 and 3. Therefore, such a question would be an important focus for future research.

Conclusion

Past research has shown that deafness contributes to changes in processing pathways in the visual modality, specifically within the dorsal visual pathway responsible for processing visual events and the location and movement of visual objects (Dye & Bavelier, 2013; Neville & Lawson, 1987b; Pavani & Bottari, 2012). However, many deaf individuals also have extensive if not lifelong experience processing a visual language. The cognitive demands to allocate attention across the visual field during sign comprehension (Bosworth et al., 2019; Stoll & Dye, 2019) may also contribute to the reorganization of visual pathways. In particular, the need to distinguish handshapes in peripheral vision during sign language comprehension may influence the ventral visual pathway that is responsible for discriminating visual forms. Indeed, we find that deaf signers show a smaller decrease in accuracy due to eccentricity when the handshapes are a component of a meaningful sign relative to a component of meaningless stimuli or in stimuli for which meaning must be mediated through a second language (e.g., English). These studies have implications for educational programs and policies serving deaf children; in addition to providing a foundational first language for deaf individuals, sign language may lead to enhancements in visual processing pathways that can then benefit linguistic processing in a second language (i.e., reading English; Bélanger et al., 2012; Bélanger et al., 2018). The current study provides a promising step in establishing peripheral processing advantages for meaningful linguistic stimuli among deaf signers.

[9] Despite this difference in perceptual features between the sign model's productions, we opted for this rather than digital reversal because the unnaturalness of the physical movements associated with digital reversal would have been more salient than the production differences produced by the model.

References

Agrafiotis, D., Canagarajah, N., Bull, D., & Dye, M. (2003). Perceptually optimised sign language video coding based on eye tracking analysis. *Electronics Letters, 39,* 1703–1705. http://dx.doi.org/10.1049/el:20031140

Aristis, S. (1986). Motion perception in the frontal plane. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human* *performance* (Vol. 1, pp. 16.1–16.27). New York, NY: John Wiley and Sons.

Arnold, P., & Murray, C. (1998). Memory for faces and objects by deaf and hearing signers and hearing nonsigners. *Journal of Psycholinguistic Research, 27,* 481–497. http://dx.doi.org/10.1023/A:1023277220438

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software, 67,* 1–48. http://dx.doi.org/10.18637/jss.v067.i01

Bavelier, D., Brozinsky, C., Tomann, A., Mitchell, T., Neville, H., & Liu, G. (2001). Impact of early deafness and early exposure to sign language on the cerebral organization for motion processing. *The Journal of Neuroscience, 21,* 8931–8942. http://dx.doi.org/10.1523/JNEUROSCI.21-22-08931.2001

Bavelier, D., Dye, M. W. G., & Hauser, P. C. (2006). Do deaf individuals see better? *Trends in Cognitive Sciences, 10,* 512–518. http://dx.doi.org/10.1016/j.tics.2006.09.006

Bavelier, D., Tomann, A., Hutton, C., Mitchell, T., Corina, D., Liu, G., & Neville, H. (2000). Visual attention to the periphery is enhanced in congenitally deaf individuals. *The Journal of Neuroscience, 20*(17), RC93. http://dx.doi.org/10.1523/JNEUROSCI.20-17-j0001.200

Bélanger, N. N., Lee, M., & Schotter, E. R. (2018). Young skilled deaf readers have an enhanced perceptual span in reading. *The Quarterly Journal of Experimental Psychology, 71,* 291–301. http://dx.doi.org/10.1080/17470218.2017.1324498

Bélanger, N. N., Slattery, T. J., Mayberry, R. I., & Rayner, K. (2012). Skilled deaf readers have an enhanced perceptual span in reading. *Psychological Science, 23,* 816–823. http://dx.doi.org/10.1177/0956797611435130

Bettger, J., Emmorey, K., McCullough, S., & Bellugi, U. (1997). Enhanced facial discrimination: Effects of experience with American sign language. *Journal of Deaf Studies and Deaf Education, 2,* 223–233. http://dx.doi.org/10.1093/oxfordjournals.deafed.a014328

Bola, Ł., Zimmermann, M., Mostowski, P., Jednoróg, K., Marchewka, A., Rutkowski, P., & Szwed, M. (2017). Task-specific reorganization of the auditory cortex in deaf humans. *PNAS Proceedings of the National Academy of Sciences of the United States of America, 114*(4), E600–E609. http://dx.doi.org/10.1073/pnas.1609000114

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,* 152–169. http://dx.doi.org/10.1006/brcg.2001.1497

Bosworth, R. G., Wright, C. E., & Dobkins, K. R. (2019). Analysis of the visual spatiotemporal properties of American Sign Language. *Vision Research, 164,* 34–43. http://dx.doi.org/10.1016/j.visres.2019.08.008

Bottari, D., Nava, E., Ley, P., & Pavani, F. (2010). Enhanced reactivity to visual stimuli in deaf individuals. *Restorative Neurology and Neuroscience, 28,* 167–179. http://dx.doi.org/10.3233/RNN-2010-0502

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research, 13,* 767–782. http://dx.doi.org/10.1016/0042-6989(73)90041-2

Boutla, M., Supalla, T., Newport, E. L., & Bavelier, D. (2004). Short-term memory span: Insights from sign language. *Nature Neuroscience, 7,* 997–1002. http://dx.doi.org/10.1038/nn1298

Cattell, J. M. (1886). The time it takes to see and name objects. *Mind, 11,* 63–65. http://dx.doi.org/10.1093/mind/os-XI.41.63

Chen, Q., He, G., Chen, K., Jin, Z., & Mo, L. (2010). Altered spatial distribution of visual attention in near and far space after early deafness. *Neuropsychologia, 48,* 2693–2698. http://dx.doi.org/10.1016/j.neuropsychologia.2010.05.016

Dye, M. W. G. (2016). Foveal processing under concurrent peripheral load in profoundly deaf adults. *Journal of Deaf Studies & Deaf Education, 21,* 122–128. http://dx.doi.org/10.1093/deafed/env054

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,* 1801–1811. http://dx.doi.org/10.1016/j.neuropsychologia.2006.12.019

Dye, M. W. G., & Bavelier, D. (2010). Attentional enhancements and deficits in deaf populations: An integrative review. *Restorative Neurology and Neuroscience, 28,* 181–192. http://dx.doi.org/10.3233/RNN-2010-0501

Dye, M. W. G., & Bavelier, D. (2013). Visual attention in deaf humans: A neuroplasticity perspective. In A. Kral, A. Popper, & R. Fay (Eds.), *Handbook of auditory research: Deafness* (pp. 237–263). New York, NY: Springer. http://dx.doi.org/10.1007/2506_2013_9

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

Emmorey, K., Bosworth, R., & Kraljic, T. (2009). Visual feedback and self-monitoring of sign language. *Journal of Memory and Language, 61,* 398–411. http://dx.doi.org/10.1016/j.jml.2009.06.001

Emmorey, K., Klima, E., & Hickok, G. (1998). Mental rotation within linguistic and non-linguistic domains in users of American sign language. *Cognition, 68,* 221–246. http://dx.doi.org/10.1016/S0010-0277(98)00054-7

Emmorey, K., Korpics, F., & Petronio, K. (2009). The use of visual feedback during signing: Evidence from signers with impaired vision. *Journal of Deaf Studies and Deaf Education, 14,* 99–104. http://dx.doi.org/10.1093/deafed/enn020

Finney, E. M., & Dobkins, K. R. (2001). Visual contrast sensitivity in deaf versus hearing populations: Exploring the perceptual consequences of auditory deprivation and experience with a visual language. *Cognitive Brain Research, 11,* 171–183. http://dx.doi.org/10.1016/S0926-6410(00)00082-3

Jordan, T. R., Patching, G. R., & Thomas, S. M. (2003). Assessing the role of hemispheric specialisation, serial-position processing, and retinal eccentricity in lateralised word recognition. *Cognitive Neuropsychology, 20,* 49–71. http://dx.doi.org/10.1080/02643290244000185

Lee, B., Meade, G., Midgley, K. J., Holcomb, P. J., & Emmorey, K. (2019). ERP evidence for coactivation of English words during recognition of American Sign Language signs. *Brain Sciences, 9,* 148. http://dx.doi.org/10.3390/brainsci9060148

Levi, D. M. (2008). Crowding—An essential bottleneck for object recognition: A mini-review. *Vision Research, 48,* 635–654. http://dx.doi.org/10.1016/j.visres.2007.12.009

Mastrantuono, E., Saldaña, D., & Rodríguez-Ortiz, I. R. (2017). An eye tracking study on the perception and comprehension of unimodal and bimodal linguistic inputs by deaf adolescents. *Frontiers in Psychology, 8,* 1044. http://dx.doi.org/10.3389/fpsyg.2017.01044

Morford, J. P., Kroll, J. F., Piñar, P., & Wilkinson, E. (2014). Bilingual word recognition in deaf and hearing signers: Effects of proficiency and language dominance on cross-language activation. *Second Language Research, 30,* 251–271. http://dx.doi.org/10.1177/0267658313503467

Morford, J. P., Occhino-Kehoe, C., Piñar, P., Wilkinson, E., & Kroll, J. F. (2017). The time course of cross-language activation in deaf ASL-English bilinguals. *Bilingualism: Language and Cognition, 20,* 337–350. http://dx.doi.org/10.1017/S136672891500067X

Morford, J. P., Wilkinson, E., Villwock, A., Piñar, P., & Kroll, J. F. (2011). When deaf signers read English: Do written words activate their sign translations? *Cognition, 118,* 286–292. http://dx.doi.org/10.1016/j.cognition.2010.11.006

Muir, L. J., & Richardson, I. E. G. (2005). Perception of sign language and its application to visual communications for deaf people. *Journal of Deaf Studies and Deaf Education, 10,* 390–401. http://dx.doi.org/10.1093/deafed/eni037

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. http://dx.doi.org/10.1016/0006-8993(87)90295-2

Neville, H. J., & Lawson, D. (1987b). Attention to central and peripheral visual space in a movement detection task: An event-related potential and behavioral study. II. Congenitally deaf adults. *Brain Research, 405,* 268–283. http://dx.doi.org/10.1016/0006-8993(87)90296-4

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. http://dx.doi.org/10.1016/0006-8993(87)90297-6

Parasnis, I., & Samar, V. J. (1985). Parafoveal attention in congenitally deaf and hearing young adults. *Brain and Cognition, 4,* 313–327. http://dx.doi.org/10.1016/0278-2626(85)90024-7

Parasnis, I., Samar, V., Bettger, J., & Sathe, K. (1996). Does deafness lead to enhancement of visual spatial cognition in children? Negative evidence from deaf nonsigners. *Journal of Deaf Studies and Deaf Education, 1,* 145–152. http://dx.doi.org/10.1093/oxfordjournals.deafed.a014288

Pavani, F., & Bottari, D. (2012). Visual abilities in individuals with profound deafness: A critical review. In M. M. Murray & M. T. Wallace (Eds.), *The neural bases of multisensory processes* (pp. 423–448). Boca Raton, FL: CRC Press.

R Core Team. (2019). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/

Reicher, G. M. (1969). Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology, 81,* 275–280. http://dx.doi.org/10.1037/h0027768

Smith, A., & Surrency, S. (2014a). *Foundations of American Sign Language Course 1*. Dubuque, IA: Kendall Hunt Pub.

Smith, A., & Surrency, S. (2014b). *Foundations of American Sign Language Course 2*. Dubuque, IA: Kendall Hunt Pub.

Stevens, C., & Neville, H. (2006). Neuroplasticity as a double-edged sword: Deaf enhancements and dyslexic deficits in motion processing. *Journal of Cognitive Neuroscience, 18,* 701–714. http://dx.doi.org/10.1162/jocn.2006.18.5.701

Stoll, C., & Dye, M. (2019). Sign language experience redistributes attentional resources to the inferior visual field. *Cognition, 191,* 103957. http://dx.doi.org/10.1016/j.cognition.2019.04.026

Stoll, C., Palluel-Germain, R., Caldara, R., Lao, J., Dye, M. W. G., Aptel, F., & Pascalis, O. (2018). Face recognition is shaped by the use of sign language. *Journal of Deaf Studies and Deaf Education, 23,* 62–70. http://dx.doi.org/10.1093/deafed/enx034

Surrency, S., & Smith, A. (2016a). *Foundations of American Sign Language Course 3*. Dubuque, IA: Kendall Hunt Pub.

Surrency, S., & Smith, A. (2016b). *Foundations of American Sign Language Course 4*. Dubuque, IA: Kendall Hunt Pub.

Swisher, M. V., Christie, K., & Miller, S. L. (1989). The reception of signs in peripheral vision by deaf persons. *Sign Language Studies, 63,* 99–125. http://dx.doi.org/10.1353/sls.1989.0011

Ungerleider, L. G., & Mishkin, M. (1982). Two cortical visual systems. In D. J. Ingle, M. A. Goodale, & R. J. W. Mansfield (Eds.), *Analysis of Visual Behavior* (pp. 549–586). Cambridge, MA: MIT Press.

Westfall, J. (2016). PANGEA: Power ANalysis for GEneral Anova designs (working paper). Retrieved from https://jakewestfall.shinyapps.io/pangea/

Wheeler, D. D. (1970). Processes in word recognition. *Cognitive Psychology, 1,* 59–85. http://dx.doi.org/10.1016/0010-0285(70)90005-8

Wilson, M., Bettger, J., Niculae, I., & Klima, E. (1997). Modality of language shapes working memory: Evidence from digit span and spatial span in ASL signers. *Journal of Deaf Studies and Deaf Education, 2,* 150–160. http://dx.doi.org/10.1093/oxfordjournals.deafed.a014321

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