Enhanced sentence processing abilities among congenitally blind adults

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Abstract

Sensory loss, such as blindness, is associated with selective improvements in intact senses and repurposing of deafferented "visual" cortex for non-visual functions. Areas within "visual" cortex are active during language tasks and show sensitivity to grammar in congenitally blind adults. Whether this plasticity confers a behavioral benefit is not known. Congenitally blind (n=25) participants and sighted (n=52) controls answered yes/no who-did-what-to-whom questions for auditorily-presented sentences, some of which contained a grammatical complexity manipulation (either a long-distance movement dependency or a garden path). Short-term memory span was measured with a forward and backward letter-span task. Participants also performed a battery of control tasks, including two speeded math tasks and standardized cognitive measures from the Woodcock Johnson III. Blind and sighted groups performed similarly on control tasks. However, the blind group performed better on sentence comprehension, particularly for garden-path sentences. Sentence-related improvement was independent of enhancement in short-term memory as measured by span tasks. These results suggest that habitual language processing in the absence of visual cues, together with availability of "visual" cortex wetware enhances sentence processing.

Keywords:

Sentence processing, blindness, garden path, plasticity, practice

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Introduction

Humans adapt flexibly to changes in experience. A key example of this adaptability comes from studies of sensory loss, such as in blindness and deafness. The loss of one modality is associated with selective improvements in perception through other modalities. Individuals who are blind from birth are better than sighted controls at judging whether an auditory pitch is falling or rising, localizing sounds in the horizontal plane and detecting orientations of tactually-presented gratings (Lessard, Pare, Lepore, & Lassonde, 1998; Goldreich & Kanics, 2003). Improvements are thought to result, in part, from practice in relying on and extracting information from non-visual senses.

Behavioral improvements associated with blindness may further be enabled by availability of extra cortical real-estate. Neuroimaging studies with blind and deaf individuals find that deprived sensory cortices—i.e., visual and auditory cortices, respectively—participate in new cognitive functions (e.g. Sadato, et al., 1996; Bavelier & Neville, 2002; Kupers & Ptito, 2014; Merabet & Pascual-Leone, 2009; Noppeney, 2007). In blindness, "visual" cortices are active during auditory and tactile tasks. Some of the tasks associated with "visual" cortex activity are the very ones on which blind individuals outperform the sighted. Visual cortices of blind individuals are active during auditory localization and fine-grained tactile discrimination (Collignon, Vandewalle, & Voss, 2011; Collignon, Voss, Lassonde, & Lepore, 2008; Gougoux, Zatorre, Lassonde, Voss, & Lepore, 2005; Kujala, Alho, Paavilainen, Summala, & Näätänen, 1992; Roder, Teder-Sälejärvi, Sterr, & Rösler, 1999; Voss, Gougoux, Zatorre, Lassonde, & Lepore, 2008; Weeks et al., 2000).

Blindness-related repurposing of "visual" cortex is not restricted to sensory processes. In congenitally blind individuals, a large subset of "visual" cortices is recruited during language tasks. Visual cortices are active during spoken sentence comprehension and the amount of activity varies as a function of meaning and syntactic structure: "visual" cortices respond more to sentences than lists of unconnected words, more to sentences than Jabberwocky, and more to Jabberwocky than to lists of non-words (e.g., glorf, blig, marp, …) (Bedny, Pascual-Leone, Dodell-Feder, Fedorenko, & Saxe, 2011; Burton, Diamond, & McDermott, 2003; Röder, Stock, Bien, Neville, & Rösler, 2002). Larger "visual" cortex responses are observed for grammatically complex sentences with a syntactic long-distance dependency (e.g., "The girl, that the boy admires, is vacationing in Spain") (Lane, Kanjlia, Omaki, & Bedny, 2015; Röder et al., 2002).

Language-responsive parts of visual cortex augment, rather than replace the classic fronto-temporal language regions, which show similar functional profiles across blind and sighted groups. Language-responsive "visual" cortex areas are collateralized with inferior frontal language regions across blind individuals and correlated with fronto-temporal language networks, even at rest (Bedny et al., 2011; Lane et al., 2015; Watkins et al., 2012). These results suggest that parts of "visual" cortex are incorporated into the language network in blindness. The behavioral relevance of this language-related plasticity remains unclear. Studies using transcranial magnetic stimulation (TMS), show that interfering with "visual" cortex function impairs performance on verb generation and Braille reading tasks (Amedi, Floel, Knecht, Zohary, & Cohen, 2004; Cohen, Celnik, Pascual-Leone, & Corwell, 1997). However, behavioral relevance to core language functions, such as sentence processing, remains uncertain. In one fMRI study blind participants who showed larger "visual" cortex responses to grammatically complex sentences also show superior performance at answering comprehension questions (Lane et al., 2015). In this experiment blind participants as a group were only marginally better than the sighted. However, behavior was measured in a noisy fMRI environment and the sample was relatively small and heterogenous (e.g. including individuals who are blind due to premature birth and a wide age range), potentially obscuring benefits associated with blindness. An outstanding question is whether blind individuals, on average, outperform the sighted on sentence processing, as they do in some auditory and tactile perception tasks.

Previous studies of language in blindness have focused on whether blind individuals have superior speech perception and word recognition abilities but have not examined higher-order aspects of language (i.e. syntax and semantics). Blind adults are, indeed, better than the sighted at identifying syllables in a task of dichotic listening (Hugdahl et al., 2004) and at identifying words under high-noise conditions (Muchnik, Efrati, Nemeth, Malin, & Hildesheimer, 1991). Two studies also suggest faster lexical access among individuals who are blind. One study found faster lexical decision times for spoken words and non-words among blind individuals (Röder, Demuth, Streb, & Rösler, 2003). Blind individuals also show a faster onset of the N400 component upon encountering an incongruent word at the end of a sentence—e.g. "Tomorrow Bobby will be ten years hill" (Roder, Rösler, & Neville, 2000). Traditionally these results have been interpreted as evidence for more efficient perceptual speech processing. However, the visual cortex plasticity data described above suggest that blind individuals may also show superior high-level linguistic abilities.

One higher-cognitive domain in which blind individuals are known to show an advantage is memory. Blind children and adults recall larger numbers of words, letters and digits over both short and long delays and more accurately reproduce the serial order of encoded words (Amedi, Raz, Pianka, Malach, & Zohary, 2003; Dormal, Crollen, Baumans, Lepore, & Collignon, 2016; Hull & Mason, 1995; Pasqualotto, Lam, & Proulx, 2013; Raz, Striem, Pundak, Orlov, & Zohary, 2007; Roder, Rösler, & Neville, 2001; Rokem & Ahissar, 2009; Swanson & Luxenberg, 2009;

Tillman & Bashaw, 1968; Withagen, Kappers, Vervloed, Knoors, & Verhoeven, 2013). Analogous to improvements observed in audition and touch, improvement in memory may result from compensatory reliance on memory in the absence of visual cues together with availability of extra "visual" cortex wetware (Raz, Striem, Pundak, Orlov, & Zohary, 2007). There is evidence that verbal memory tasks activate visual cortex and amount of activity predicts memory performance among blind individuals (Amedi et al., 2003; Raz, Amedi, & Zohary, 2005).

The goal of the current study was to ask whether blind individuals develop superior spoken sentence processing abilities and, if so, whether these improvements are related to previously reported advantages in verbal short-term memory among blind individuals. We measured accuracy and reaction time while blind individuals answered yes/no comprehension questions based on spoken sentences that varied in syntactic complexity. Syntactic complexity was manipulated in two independent ways, by introducing syntactic movement and using garden paths (See Table 1 for example stimuli). Sentences with syntactic movement displace referents with respect to their modifying phrase. For example, in "The actress that the creator of the gritty HBO crime series admires often improvises her lines," the object "actress" is displaced from the verb "admires." Garden path sentences are a form of temporary syntactic ambiguity in which the listener is lead to an erroneous syntactic parse that later turns out to be incorrect. For example, in "While the little girl dressed the doll that she was playing with sat on the floor of her bedroom," the initial interpretation that the girl dressed the doll turns out to be incorrect, rather the girl dressed herself. The verb "dressed" is most often followed by its object, but in this particular case is being used reflexively. Performance of blind and sighted participants on syntactically complex sentences was compared to matched control sentences. We hypothesized that blind individuals would show superior sentence-comprehension ability relative to the sighted and that this advantage would be most pronounced for syntactically complex sentences.

We measured short term memory for spoken letters, in blind and sighted participants. The goal was to replicate the previous finding that blind participants show enhancements in verbal working memory and to determine whether these enhancements are related to improvements in language or non-verbal executive control (Amedi et al., 2003; Hull & Mason, 1995).

Blind and sighted participants were also tested on a series of control tasks, including two symbolic math tasks and verbal portions of the Woodcock-Johnson III, which test vocabulary and reading ability. These tasks enabled us to test the specificity of sentence processing enhancements. We predicted that sentence-processing advantages and working memory advantages in blind individuals would persist, even when blind and sighted groups are matched on other cognitive abilities.

Methods

Participants.

25 congenitally blind individuals (15 female) and 52 sighted age and educated matched controls (36 female) took part in the study (age: blind mean=32.64, SD=9.86; sighted mean=33.31, SD=11.51; blind vs. sighted t(75)=-0.25, p=0.80; years of education: blind mean=16.68, SD=2.61, sighted mean=16.59, SD=2.20; blind vs. sighted t(75)=0.15, p=0.88). All but one blind and one sighted participant completed all of the experimental tasks. One blind participant was not tested on the Analogies and Division portions of WJIII and one sighted participant did not perform the working memory task. An addition 2 blind and 2 sighted participants were tested but excluded for poor performance on the Woodcock-Johnson III (outliers on any individual measure, defined according to Rosner's extreme studentized deviate test for multiple outliers, two-sided, $p < 0.05$, maximal 10 (Rosner, 1975)). Reported numbers of blind and sighted participants do not include these excluded participants.

All participants were native English speakers, majority having spoken only English since birth. 1 (of 25) blind and 3 (of 52) sighted learned English through emersion between 3 and 4 years of age. We collected data from blind participants at two separate conventions of the National Federation for the Blind (2014 and 2016). Sighted participants were tested at Johns Hopkins University. Blind participants had minimal-to-no light perception since birth, due to pathologies in or anterior to the optic chiasm (see Table 2 for cause of blindness). Since premature birth can be associated with cognitive disabilities, participants who were blind due to retinopathy of prematurity (ROP) were not recruited for this study (Dann, Levine, & New, 1964). All participants reported no cognitive or neurological disabilities.

To match visual conditions across groups, sighted participants were blindfolded for all tasks except for the participant-read portions of the Woodcock Johnson-III (WJ-III). Participants listened to all auditory tasks via headphones. Volume was adjusted for each participant, according to their own comfortable listening volume. All experiments were run using either PsychoPy or Matlab's Psychtoolbox (Brainard, 1997; Peirce, 2007).

Sentence Processing Task: Materials and Procedure

Each participant listened to 180 sentences and answered a yes/no comprehension question for each sentence (see Appendix 1). Participants had 6 seconds from the onset of the question to make a button press.

The syntactic complexity of sentences was manipulated in two ways: by introducing a long-distance movement dependency or a garden path syntactic ambiguity (described in detail below). Each of these two conditions was paired to a matched, control condition that lacked the critical syntactic manipulation—i.e. no-move and non-garden path sentences (see Table 1). In addition to the critical sentences, we included filler sentences to reduce syntactic priming. Fillers varied in their grammatical constructions and did not contain either long-distance dependencies or garden paths. Overall there were 120 move/no-move sentence pairs (every participant heard 60 of each version), 10 garden path, 10 non-garden path, and 40 filler sentences. A subset of initial participants (5 blind and 13 sighted; proportion of total approximately matched across groups) received a longer version of the paradigm with 248 total questions, consisting of 84 move, 84 no-move, 10 garden path, 10 non-garden path, and 60 filler trials. The experiment was subsequently shortened to reduce testing time. To control for item effects, only the items that appeared in the short-form were analyzed— i.e., 60 of 84 move and 60 of 84 non-move— even for those participants who received the longer version of the paradigm.

Sentences with syntactic movement contain words or phrases that are displaced, or "moved," with respect to their modifying phrases (See Table 1 for example sentences). Syntactic movement was achieved via object-extracted relative clauses, where the "actress," as the object of the verb "admires," is extracted from its normal position after the transitive verb and moved to the head of the relative clause. The non-movement counterpart used a sentential complement clause structure, which was similar in meaning to the relative clause version and contained nearly identical words but did not include a long-distance movement dependency. Matched movement and non-movement sentences were counterbalanced across two lists, such that each participant heard only one version of the sentence. Comprehension questions required participants to attend to thematic relations of words in the sentence (i.e., who did what to whom), and could not be answered based on recognition of individual words. Half of the move and half of the non-move stimuli had comprehension questions in which "yes" was the correct response. The stimuli were a subset of those used in a previously published study (Lane et al., 2015).

The second type of syntactic complexity manipulation was garden path, i.e. temporary syntactic ambiguities, where the listener is led down a "garden-path" in which an initially favored sentence parse turns out to be irreconcilable with subsequent words in the sentence. (Garden path and non-garden-path control sentences were adapted from a published set of stimuli (Christianson et al., 2001)). For example, in "While the little girl dressed the doll that she was playing with sat on the floor of her bedroom.," "dressed" could either be used transitively with "the doll" as the direct object (i.e. the little girl dressed the doll) or reflexively (i.e. the little girl dressed *herself*). The former interpretation is favored due to its higher subcategorization frequency, but the subsequent verb "sat" requires "the doll" to be its subject, and hence disambiguates the two alternatives in favor of the reflexive form. A relative clause modifier was added to the critical, ambiguous noun phrase in order to amplify the garden-path effect (Christianson, Hollingworth, Halliwell, & Ferreira, 2001; Ferreira & Henderson, 1991). Thus, all garden path sentences were of the following form: While [Noun Phrase 1] [Reflexive Verb] [Noun Phrase 2] [Verb Phrase]. Non-garden path control sentences were formatted as follows: While [Noun Phrase 1] [Transitive Verb] [Noun Phrase 2] [Noun Phrase 3] [Verb Phrase]. In the control sentences, the additional [Noun Phrase 3] requires the ambiguous verb to be transitive, consistent with the listener's initial parse. The non-garden-path control sentences were not yoked to their garden path counterparts (i.e. had different words), but followed the same structure templates, with the exception of the additional Noun Phrase in non-garden path sentences. All questions tested correct comprehension of the verb, in the format: Did [Noun Phrase 1] [Reflexive/Transitive Verb] [Noun Phrase 2]? For example, "Did the little girl/nanny dress the doll/baby?" Therefore, the correct response for garden path and non-garden path control questions was always "no" and "yes," respectively. All subjects heard all garden-paths and non-garden-path control sentences.

Condition ordering, across trials, was pseudo-randomized such that each condition could not appear in more than 2 contiguous trials, and the conditions were evenly dispersed across each 1/8th block of the experiment. Altogether, for half of the trials the correct response was "yes." Before starting, all participants performed a set of 10 practice trials with feedback. Sentences were pre-recorded and spoken by a male voice in a flat intonation, in order to minimize cues to correct syntactic parsing.

We removed all trials in which a participant either failed to respond or false started (i.e. responded in < 150 MS). On average, blind and sighted participants missed fewer than 1 question per each condition (overall misses: mean blind 1.48 items; mean sighted 1.92 items; n.s.

difference between groups t(75)=0.92, p =0.36). Sighted participants had more missed responses than blind participants, but this difference was not significant (move: t(75)=0.66, p>0.5; non-move: t(75)=1.25, p=0.21; garden-path: t(75)=1.75, p=0.08; non-garden path: t(75)=0.61, p>0.5). The dependent measure was accuracy (binary success or failure on each trial) and speed (reaction-time, from question onset, for correct trials only).

Working Memory Tasks

Forward and Backward Letter Span tasks were adapted from the Forward and Backward Digit Span components of the Wechsler Adult Intelligence Scale (WAIS) by mapping the digits 1-9 to the letters A-I. For both letter span tasks, participants listened to a recording of a female speaking a series of letters. After the last presented letter, participants were asked to repeat all letters back to the experimenter in either the exact order (Forward) or the exact opposite order (Backward). Trials were presented according to span-length, starting with a length of 2 and going up to 9 (for Forward) and 8 (for Backward), with 2 trials for each span length. Failure to get both trials of a given span length correct terminated the task. Accuracy was calculated as a percentage correct out of all possible trials, with incorrect recall assumed for un-tested spans. All participants did the Forward Letter Span followed immediately by the Backward Letter Span.

Woodcock-Johnson III (Control)

We collected control measures to ensure that blind and sighted groups did not differ on general cognitive abilities. Participants were tested on 5 sections of the Woodcock-Johnson III (WJ-III). Blind participants completed the WJIII in printed Braille. The following sections were tested: Letter-Word Identification in which the participant are asked to read and correctly pronounce 60 English words (e.g. “bouquet”); Word Attack in which the participant read and correctly pronounce 33 nonsense words (e.g. “paraphonity”); Oral Vocabulary-Synonyms in which the participant read each of 12 words and generate a synonym (e.g. “wild” → “untamed”); Oral Vocabulary-Antonym in which the participant read each of 13 words and generate an antonym (e.g. “authentic” → “fake”); and Oral Vocabulary-Analogies in which participants read each of 12 incomplete analogies and generate a word analogous to the unpaired word according to the relationship established by the first word pair (e.g. “Wrist is to shoulder, as ankle is to …” → “hip”). Participants were allowed to skip any items they could not complete but were not allowed to go back. Responses were considered correct if they matched one of the words designated by the WJ-III. Accuracy for each section was scored as percentage correct of all trials. All participants performed the WJ-III sections in the order listed above.

Arithmetic (Control)

Participants were tested on speeded arithmetic calculations in 2 separate tasks: subtraction and division. All problems contained 2 operands, with the following digit lengths: minuends and subtrahends (2), divisors (1), and dividends (2-3). For each task, participants were given 4 minutes to accurately complete as many problems as possible. (Participants were allowed to complete any problems begun before the 4 minutes had expired.) Problems were pre-recorded to minimize differences in presentation between participants. Participants pressed a button to initiate auditory presentation of each problem and had to state their answer to the researcher. Participants could choose to skip problems and to repeat auditory presentation of the current problem but were not allowed to go back to skipped problems. Participants were not allowed to use writing devices to solve the problems. The subtraction and division sections contained 30 and 33 problems, respectively. Accuracy was scored as percentage correct of all trials, regardless of whether they were attempted. All participants performed the subtraction task immediately before the division task. Problems were taken from the Kit of Factor-Referenced Cognitive Tests (Ekstrom, French, Harman, & Dermen, 1976).

Results

Sentence Comprehension

We compared performance across groups for the movement and garden path manipulations. For all accuracy analyses, we used a mixed-effect generalized-linear (logit) model with participant and item included as random effects (Baayen, Davidson, & Bates, 2008; Clark, 1973; Jaeger, 2008). For all reaction time analyses, we used a mixed-effect general linear model with participant and item included as random effects. Due to differing numbers of trials across movement and garden-path sentences, we analyzed them separately and compared each to their respective control sentences.

Blind participants were overall more accurate for both move and non-move control sentences (sighted non-move mean=86.61%, SD=8.74%; sighted move mean=74.53%, SD=11.63%; blind non-move mean=90.16%, SD=6.69%; blind move mean=80.91%, SD=8.91%; group X complexity ANOVA, main effect of group, log-odds coefficient B=0.39 (SE=0.16), p=0.014; corresponding odds coefficient e^B=1.48). For both blind and sighted participants, accuracy was worse for move sentences than for non-move sentences (main effect of complexity, log-odds coefficient B=0.90 (SE=0.12), p<0.001; corresponding odds coefficient e^B=2.46, n.s. group X complexity interaction, log-odds coefficient B=-0.06 (SE=0.13), p>0.5; corresponding odds coefficient e^B=0.94) (Figure 1, left panel).

Better accuracy of the blind group for move and non-move sentences was not driven by a speed-accuracy tradeoff (Figure 1, right panel). Rather, blind participants were slightly, but not significantly, faster at responding than sighted participants (sighted non-move mean=3.37 s, SD=0.27 s; sighted move mean=3.48 s, SD=0.26 s; blind non-move mean=3.29 s, SD=0.26 s;

blind move mean=3.42 s, SD=0.30 s; group X complexity ANOVA: n.s. main effect of group, B=-0.07 (SE=0.06), p=0.28, n.s. group X complexity interaction, B=0.1 (SE=0.03), p>0.5). Both groups responded to move sentences more slowly than to non-move sentences (main effect of sentence-type, B=-0.12 (SE=0.03), p=0.001).

Blind participants were overall more accurate across garden-path (blind mean=76.00%, SD=27.08%; sighted mean=56.99%, SD=30.18%) and control sentences (blind mean=96.00%, SD=7.07%; sighted mean=91.80%, SD=8.43%; group X complexity ANOVA: main effect of group, log-odds coefficient B=1.03 (SE=0.39), p=0.008, corresponding odds coefficient e^B=2.79). Although the group difference was numerically more pronounced for the garden-path sentences, the group-by-sentence type interaction did not reach significance (group X complexity interaction, log-odds coefficient B=-0.28 (SE=0.43), p>0.5; corresponding odds coefficient e^B=0.75). Accuracy was worse for garden path than non-garden path control sentences for both groups (main effect of complexity, log-odds coefficient B=2.74 (SE=0.47), p<0.001; corresponding odds coefficient e^B=15.49).

Blind participants were overall faster than the sighted to answer questions about garden-path and non-garden path control sentences and in this case the main effect of group was qualified by a group-by-condition interaction: While sighted participants were slower to respond to garden-path than non-garden path sentences, blind participants responded with equal speed to both sentence types (sighted non-garden path mean=2.87 s, SD=0.22 s; sighted garden path mean=3.09 s, SD=0.42 s; blind non-garden path mean=2.84 s, SD=0.20 s; blind garden path mean=2.84 s, SD=0.44 s; group X complexity ANOVA, main effect of group, B=-0.14 (SE=0.06), p=0.03, group X complexity interaction, B=0.22 (SE=0.06), p=0.001; n.s. main effect of sentence-type, B=-0.07 (SE=0.14), p> 0.5).

Since all garden-path sentences required a “no” response, we checked if group differences in response-bias might have driven the observed difference in performance. We measured bias to respond “no” for difficult questions as the percentage of “no” responses on incorrect move, non-move, and filler items. Blind participants were not more biased to respond “no” (n.s. difference between groups: $t(75)=1.01$, $p=0.31$)

WJ-III & Arithmetic (Control)

Blind and sighted participants performed equivalently on the WJ-III subsections (group X WJ-III measure ANOVA, main effect of group not significant, $F(1,74)=0.05$, $p>0.5$; group X measure interaction not significant, $F(4,296)=0.49$, $p>0.5$) (Figure 2). For the math tasks, a group by operation (division vs. subtraction) ANOVA revealed a main effect of math operation with division more difficult than subtraction, $F(1,74)=185.81$, $p < 0.001$). Overall, blind and sighted participants did not differ in their math performance (main effect of group not significant, $F(1,74)=1.29$, $p=0.26$). However, there was a significant interaction between group and math-operation with blind participants showing a bigger differences between subtraction and division tasks ($F(1,74)=7.05$, $p=0.01$) (Figure 2).

Working Memory Span

A group X direction (forward vs. backward) ANOVA, revealed a main effect of span direction, with forward span significantly easier than backward span ($F(1,74)=13.70$, $p<0.001$) (Figure 2, right-most columns). Across spans, blind participants had better working memory than sighted participants (main effect of group, $F(1,74)=33.21$, $p<0.001$; n.s. group X direction (forward vs. backward) interaction, $F(1,74)=0.94$, $p=0.34$).

Relationship between Short-term Memory Span and Sentence Comprehension

Short-term memory span did not significantly predict sentence comprehension performance in either the blind or the sighted groups for any sentence types (correlation with average forward & backward span: blind accuracy: move: r=0.31, p=0.13, non-move: r=0.31, p=0.12, garden path: r=0.28, p=0.17, non-garden path: r=0.33, p=0.10; sighted accuracy: move: r=0.17, p=0.23, non-move: r=0.17, p=0.23, garden path: r=0.17, p=0.24, non-garden path: r=0.16, p=0.28) (Figure 3).

Short-term memory span also did not significantly predict sentence comprehension response times in either the blind or the sighted group for any sentence types (correlation with average forward & backward span: blind RT: move: r=-0.23, p=0.27, non-move: r=-0.20, p=0.35, garden path: r=-0.18, p=0.38, non-garden path: r=-0.04, p>0.5; sighted RT: move: r=-0.09, p>0.5, non-move: r=-0.26, p=0.07, garden path: r=0.11, p=0.45, non-garden path: r=0.02, p>0.5).

Discussion

Blindness confers an advantage to sentence processing, how and why?

We find that congenitally blind individuals are more accurate than matched, sighted controls at answering who-did-what-to-whom questions about sentences. Blind participants are also faster and particularly for garden-path sentences: Unlike sighted adults, blind individuals responded as quickly to questions about garden-path sentences as they do to matched, non-garden-path control sentences, showing no garden path cost in reaction time. The advantage in sentence processing cannot be explained by differences in general cognitive abilities across groups: blind participants performed no better than sighted participants on standardized tasks assessing reading, vocabulary, analogies, and arithmetic. Though blind participants outperformed the sighted on forward and backward letter span tasks, letter-span and comprehension performance were not correlated.

As noted in the introduction, unlike the sighted, blind individuals recruit "visual" cortices during sentence processing tasks and more so for syntactically complex sentences (Bedny et al., 2011; Lane et al., 2015; Röder et al., 2002). Larger "visual" cortex responses are associated with better sentence comprehension performance across blind individuals (Lane et al., 2015). TMS to "visual" cortex impairs verb-generation and Braille reading among blind individuals (Amedi et al., 2004, Cohen et al., 1997). Together with the present results, these findings are consistent with the hypothesis that extra "visual" cortex plasticity contributes to the behavioral advantage in language processing. However, further work using techniques such as TMS is needed to directly test the hypothesis that "visual" cortex is functionally relevant to sentence-processing per se.

The availability of “visual” cortex territory is only one of several non-mutually exclusive reasons for why blindness might show enhanced sentence processing. Vision and language often provide analogous information about the identity of objects and agents and about who did what to whom. There is extensive evidence that linguistic and visual information is rapidly integrated during online comprehension to build situation models. According to constraint-based models of sentence processing, comprehension occurs by integrating various sources of information, including not only syntactic and lexical information, but also extra-linguistic cues such as what objects are present in the environment (Bader, 1998; Bailey & Ferreira, 2003; Chambers, Tanenhaus, Eberhard, Filip, & Carlson, 2002; MacDonald, Pearlmutter, & Seidenberg, 1994; McRae, Spivey-Knowlton, & Tanenhaus, 1998; Nagel, Shapiro, & Nawy, 1994; Tanenhaus, Magnuson, Dahan, & Chambers, 2000; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995; Trueswell & Gleitman, 2004; Trueswell, Tanenhaus, & Garnsey, 1994; Tyler & Marslen-Wilson, 1977). For example, sighted listeners rapidly use visual cues to disambiguate temporarily ambiguous garden-path sentences, using the number and location of objects present to determine whether a propositional phrase indicates a destination or a modifier of the preceding noun “put the frog on the napkin, into the box” (Chambers, Tanenhaus, & Magnuson, 2004; Farmer, Anderson, & Spivey, 2007; Huettig, Rommers, & Meyer, 2011; Spivey, Tanenhaus, Eberhard, & Sedivy, 2002; Tanenhaus et al., 1995). Although audition and touch also contain relevant contextual information, vision may be a particularly efficient source of information about the types of things that language refers to: object and agent identity, their location and the events in which they participate. While sighted individuals may habitually depend on extralinguistic information during comprehension, blind individuals may develop better abilities to use language-internal information during sentence parsing. Such a practice-based enhancement could be thought of as analogous to better attention to, and extraction of, information from audition and touch (Fieger, Röder, Teder-Sälejärvi, Goldreich & Kanics, 2003; Hillyard, & Neville, 2006; Lessard, Pare, Lepore, & Lassonde, 1998; Van Boven, Hamilton, Kauffman, Keenan, & Leone, 2000; Voss et al., 2004; Wan, Wood, Reutens, & Wilson, 2010; Wong, Gnanakumaran, & Goldreich, 2011). Blind participants may therefore perform better when extralinguistic cues are absent for both groups, as was the case in the current study.

The above practice-based argument is not inconsistent with the hypothesis that “visual” cortex plasticity enables behavioral improvements. The availability of extra language wetware in the “visual” cortex could make behavioral improvements possible in the presence of pressure from the environment to acquire them. Conversely, reliance on language as a source of information may increase pressure for language (as opposed to other cognitive functions) to colonize available territory in the “visual” cortex.

What cognitive mechanisms are responsible for the observed sentence processing improvements? One logical possibility is that improvements are related to previously documented enhancements in short-term memory associated with blindness (Amedi, et al., 2003; Hull & Mason, 1995; Raz et al., 2007; Rokem & Ahissar, 2009; Tillman & Bashaw, 1968; Withagen et al., 2013). Consistent with this prior work, blind participants in the current study performed significantly better than the sighted on forward and backward short-term memory tasks. However, we find that sentence-processing and short-term memory improvements observed in blindness are independent: blind individuals that show the largest improvements in sentence processing are not the same as those who show maximal improvement in short-term memory. This result suggests that superior sentence processing abilities are not related to improvements in short-term memory functions that are measured by span tasks.

Nevertheless, improvements in short-term memory and sentence processing could still occur for analogous reasons. Blind individuals may be better at maintaining linguistic information active during parsing, even if this sentence-relevant short-term memory system is distinct from the one used during simple short-term memory span tasks (Caplan & Waters, 1999). As a sentence unfold in time, listeners maintain previously heard linguistic information and blind listeners may maintain more of this information, with higher fidelity and perhaps for a longer amount of time. For sentences with a movement dependency, blind individuals may be better able to maintain information before it can be integrated into the sentence structure. For example, maintaining the matrix subject in memory across the intervening clause until the associated relative clause verb is encountered. In the case of garden path sentences, blind individuals may maintain the initially dis-preferred sentence parse active to greater extent than sighted participants (Gibson, 1998; Hickok, 1993; Just & Carpenter, 1992; MacDonald et al., 1994; McRae et al., 1998; Stevenson, 1998). If so, when this dis-preferred parse turns out to be the correct one, blind individuals would show a reduced performance cost. An alternative possibility, is that blindness improves executive function mechanisms that are involved in selection of the preferred sentence interpretation in the context of syntactic ambiguity (January, Trueswell, & Thompson-Schill, 2009; Novick et al., 2012; Novick, Trueswell, & Thompson-Schill, 2005; 2010; Thompson-Schill, Bedny, & Goldberg, 2005; Woodard, Pozzan, & Trueswell, 2016). Finally, it may be that some of the observed benefits are related to blind people’s enhanced ability to use subtle prosodic cues to arrive at the correct parse. The stimuli used in the current study were intentionally recorded to lack such cues but may not fully avoided them. In sum, blindness seems to improve the ability to use language-internal information to arrive at the correct sentence interpretation. Future work should tease apart the precise cognitive mechanism that supports this improvement.

Testing blind participants on a larger battery of linguistic and higher-cognitive tasks could provide insight into the precise mechanism of blindness-mediated improvements in language processing. For example, if blindness enhances selection mechanisms that are involved in sentence comprehension, we would predict that blind individuals would show superior performance at other tasks involving ambiguity resolution (e.g. interpreting homonymous words) and perhaps even some non-verbal inhibitory tasks i.e. auditory STROOP. In contrast, if the enhancements are mediated by sentence-specific maintenance mechanisms we would not expect advantages in lexical tasks, whether they involve ambiguity or not. It further remains possible that blindness independently enhances multiple different aspects of linguistic processing (e.g. sentence processing, morphological processes, lexical retrieval).

An open question is whether other types of variation in experience, apart from blindness, could improve human capacity to make better use of language internal information and if so whether behavioral improvements would occur even in the absence of extra available visual cortex "wetware" i.e. in the sighted. Efforts to train sighted speaker to become better at parsing complex sentences in the laboratory have met with mixed success. One study reported that successful training on a demanding N-back task improved performance on syntactically ambiguous sentences (Novick, Hussey, Teubner-Rhodes, Harbison, & Bunting, 2012). Some studies suggest that experience with particular types of grammatical constructions enhances performance with those constructions (Fine, Jaeger, Farmer, & Qian, 2013; Long & Prat, 2008; Roth, 1984; Wells, Christiansen, Race, Acheson, & MacDonald, 2009). However, the improvements specific to trained sentence constructions (Long & Prat, 2008; Roth, 1984; Wells et al., 2009). Blindness-related improvements in sentence-processing may be more general either because blindness causes more extensive, naturalistic and varied “training” or because of the availability of a distinct neural mechanisms. In future work it would be interesting to test whether other naturalistic experiences, such as extensive reading or extensive listening to audiobooks, would improve sentence processing.

Conclusions

The present results suggest that blindness leads to independent advantages in sentence processing and short-term memory. These improvements are analogous to previously reported blindness-related advantages in audition and touch (Fieger et al., 2006; Lessard et al., 1998; Rice, 2017; Roder et al., 1999; Voss et al., 2004). Lack of visual experience enhances not only perception through other senses, but also higher cognitive abilities that can be used to achieve similar behavioral goals, including language. These results suggest that individual variation in non-linguistic experience can enhance the capacity of the language system to function in the absence of extrinsic cues.

Appendix A.

All sentences and probe questions for garden path and non-garden path conditions, as well as a sample of syntactic movement and non-movement conditions. A complete list of stimuli as well as their audio recordings have been uploaded with the submission and will be available at Open Science Framework osf.org.

<u>Garden Path</u>

1. While the cat groomed the little kittens explored the living room and clawed the furniture.
   Did the cat groom the kittens?
2. While the chimpanzees groomed the baboons that were large and hairy sat in the grass and played with sticks.
   Did the chimpanzees groom the baboons?
3. While the little girl dressed the doll that she was playing with sat on the floor of her bedroom.
   Did the little girl dress the doll?
4. While the surgeon shaved the patient who was exhausted and weak from the operation watched television.
   Did the surgeon shave the exhausted patient?
5. While the barber shaved his customer walked into the shop and sat down by the window.
   Did the barber shave his customer?
6. While the French woman bathed her new puppy that she adopted from the shelter chewed on the TV remote.

Did the French woman bathe her new puppy?

7. When the grandparents woke up their three grandchildren were racing around the house playing tag.

   Did the grandparents wake up the grandchildren?

8. While the thief hid the jewelry that was elegant and expensive sparkled brightly on the counter.

   Did the thief hide the elegant jewelry?

9. While the mother undressed the baby that was bald and helpless cried softly because she was hungry.

   Did the mother undress the baby?

10. While the frightened woman hid her family's precious heirlooms from the Civil War era were discovered by the burglars.

    Did the frightened woman hide the heirlooms?

<u>Non-Garden Path</u>

1. While the nanny dressed the baby that was small and cute the baby's mother was in the kitchen preparing dinner.

   Did the nanny dress the baby?

2. While the father bathed the child that was blond and pudgy the baseball game played on the radio.

   Did the father bathe the child?

3. While the jockey tried to settle down the thoroughbred horse that was eager to run the trainer observed and said nothing.

Did the jockey try to settle down the horse?

4. While the mother tried to calm down the children who were irritable her husband left to pick up a pizza.

   Did the mother try to calm down the children?

5. While the painters washed the dirty paint brushes that were sitting on the floor the homeowner inspected their work.

   Did the painters wash the paint brushes?

6. While the car wash employee dried off the car that was red and shiny the owner fixed a cup of coffee.

   Did the car wash employee dry off the car?

7. While the veterinarian dried off the cow that had been in the rainstorm the baby calf chewed some grass.

   Did the veterinarian dry off the cow?

8. When the woman woke up the next-door neighbor who is a cranky Army veteran he threatened to call the police.

   Did the woman wake up the next-door neighbor?

9. While the theme park attendant tried to calm down the angry family shouting at him the line kept getting longer.

   Did the attendant try to calm down the family?

10. While the overnight mall employee undressed the mannequin in the hallway she thought about her upcoming vacation.

    Did the employee undress the mannequin?

Syntactic Movement/Non-Movement

1. The architect that the tough fireman at the end of the bar dislikes always has to be the center of the conversation. (Move)

   The tough fireman at the end of the bar dislikes that the architect always has to be the center of the conversation. (No-Move)

   Is it the fireman who has to be the center of conversation?

2. The accountant that the corrupt detective in the organized crime division dislikes advises the Sicilian mob. (Move)

   The corrupt detective in the organized crime division dislikes that the accountant advises the Sicilian mob. (No-Move)

   Is it that the accountant advises the mob?

3. The paramedic that the exhausted surgeon at the trauma center criticized gave the patient too much painkiller. (Move)

   The exhausted surgeon at the trauma center criticized that the paramedic gave the patient too much painkiller. (No-Move)

   Was it that the paramedic criticized the surgeon?

4. The telemarketer that the neurotic secretary with the messy cubicle hates clips coupons with the dull scissors. (Move)

   The neurotic secretary with the messy cubicle hates that the telemarketer clips coupons with the dull scissors. (No-Move)

   Is it the telemarketer who clips coupons?

5. The skilled editor that the politician with strong connections at the newspaper recommended changed jobs. (Move)

The politician with strong connections at the newspaper recommended that the skilled editor change jobs. (No-Move)

Is it the editor who has connections at the newspaper?

6. The public official that the newly elected district attorney cautioned was under federal investigation. (Move)

   The newly elected district attorney cautioned that the public official was under federal investigation. (No-Move)

   Is it that the public official is behind in the polls?

7. The mountain biker that the experienced climber on the rescue team yelled at fell off of the narrow trail. (Move)

   The experienced climber on the rescue team yelled that the mountain biker fell off of the narrow trail. (No-Move)

   Was it that the mountain biker fell off of the trail?

8. The child near the track that the Italian race car driver on his final lap saw wasn't paying any attention. (Move)

   The Italian race car driver on his final lap saw that the child near the track wasn't paying any attention. (No-Move)

   Was it the driver who wasn't paying attention?

9. The bold astronaut that the captain of the orbiting space ship believed in had returned from the alien planet. (Move)

   The captain of the orbiting space ship believed that the bold astronaut had returned from the alien planet. (No-Move)

   Was the astronaut described as bold?

10. The park ranger that the camera-man from the nature channel was motioning at had stumbled into a bear's den. (Move)

The camera-man from the nature channel was motioning that the park ranger had stumbled into a bear's den. (No-Move)

Was it the camera-man who stumbled into the den?

Figures.

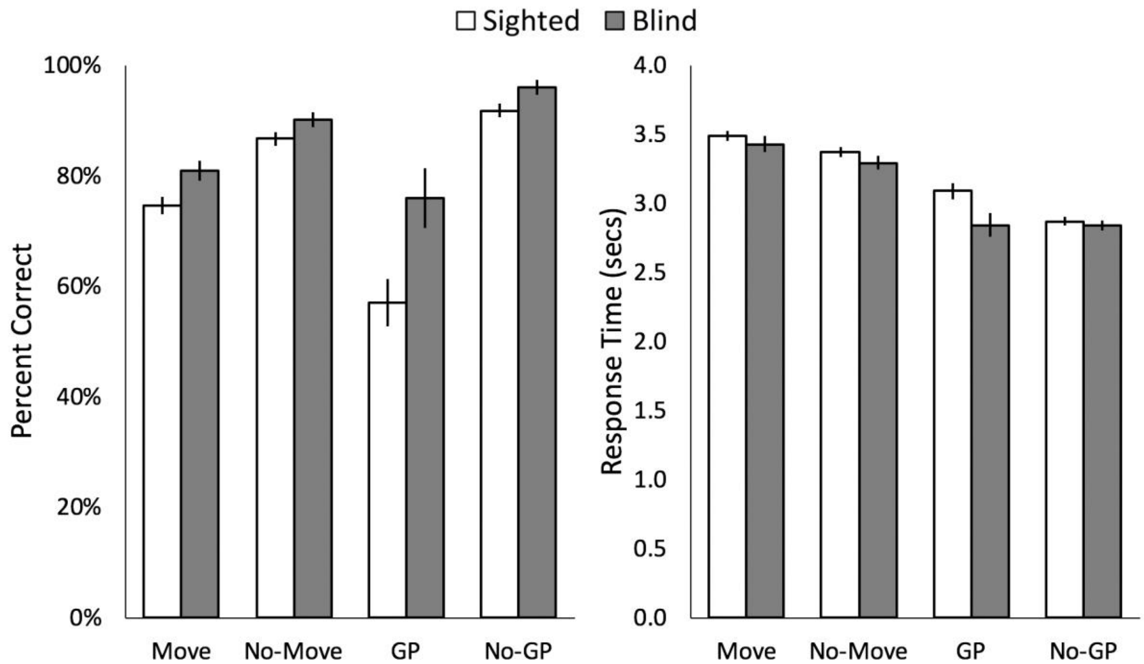

Figure 1.

Mean accuracy (left) and response times (right) for sighted and blind participants in syntactic movement (Move), matched non-movement (No-Move), garden path (GP) and matched non-garden path (No-GP) sentences. Error bars reflect SEM.

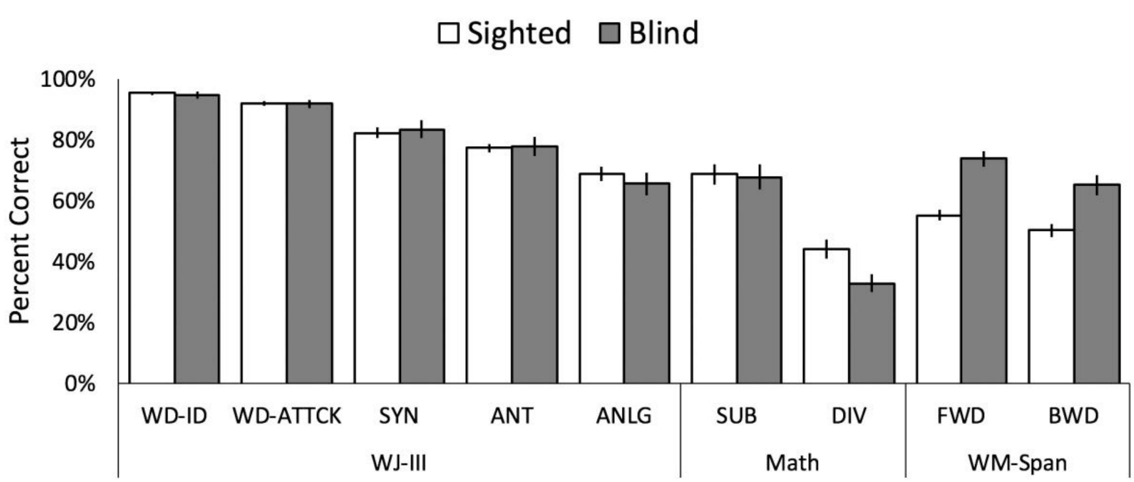

Figure 2.

Mean accuracy of sighted and blind participants in Woodcock-Johnson III measures—Word Letter Identification (WD-ID), Word Attack (WD-ATTCK), Synonyms (SYN), Antonyms (ANT), and Analogies (ANT), arithmetic—subtraction (SUB) and division (DIV), and short-term memory span—forward (FWD) and backward (BWD). Error bars reflect SEM.

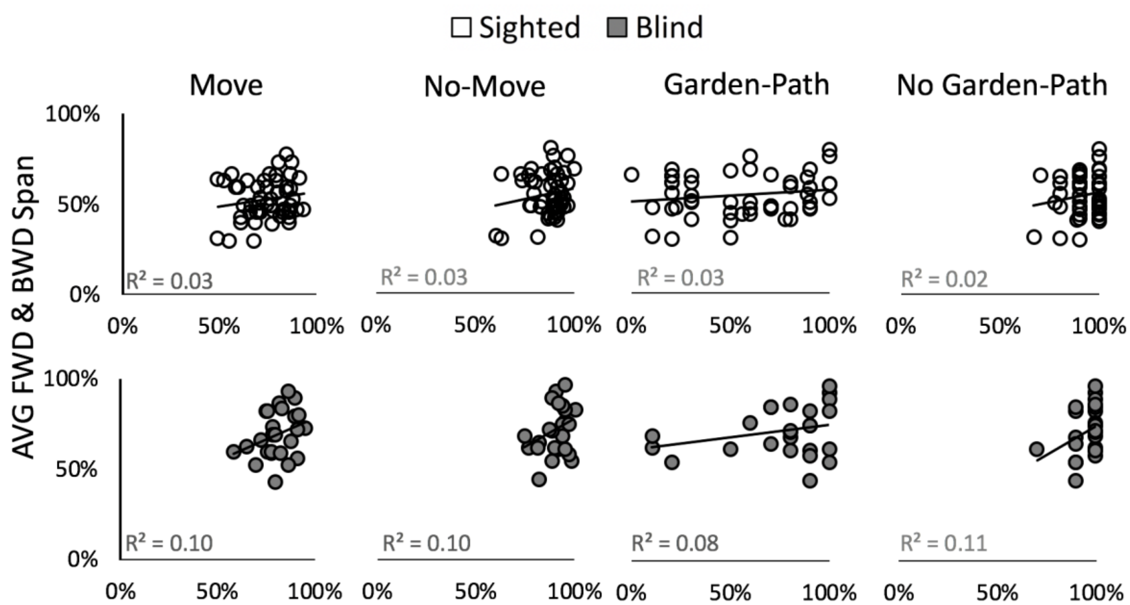

Figure 3.

Sighted (top) and blind (bottom) participants' mean forward and backward letter span accuracy correlated with their accuracy in each sentence condition (move, no move, garden path, no garden path).

Table 1.

Sample stimuli

Move	The actress that the creator of the gritty HBO crime series admires often improvises her lines.
No-Move	The creator of the gritty HBO crime series admires that the actress often improvises her lines.
Garden-Path	While the little girl dressed the doll that she was playing with sat on the floor of her bedroom.
No Garden-Path	While the nanny dressed the baby that was small and cute the baby's mother was in the kitchen preparing dinner.
Filler	The precocious child thought that that the rude waitress's purple cotton dress and orange shoes clashed horribly.

Table 2.

Number of participants per cause of blindness

Blindness Etiology	**N**	**N LP**
Leber Congenital Amaurosis	9	5
Glaucoma	3	1
Optic Nerve Hypoplasia	6	1
Anopthalmia	3	0

Micropthalmia	2	0
Retinal Blastoma	1	1
Septo-optic dysplasia	1	0

Number of participants per cause of blindness (N) and with light perception (N LP).

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