Title

Superior Verbal but Not Nonverbal Memory in Congenital Blindness

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Abstract

222 word abstract

Blind individuals rely on memory to complete some tasks that sighted individuals achieve using visual cues. For example, rather than relying on vision to locate items, blind individuals might remember items' location. Likewise, while sighted people have ready access to printed material, written braille materials are often unavailable (e.g., braille food menus). In such situations, blind individuals listen to a verbal list and hold the information in memory until it is needed. Previous studies suggest that people who are congenitally blind outperform sighted people on memory tasks. Whether blindness-associated memory advantages are specific to verbal materials or are also observed with nonverbal sounds has not been determined. Congenitally blind individuals (n=20) and age and education matched blindfolded sighted controls (n=22) performed a series of auditory memory tasks. These included verbal forward and backward letter spans, a complex letter span, as well as two matched recognition tasks: one with verbal stimuli (i.e., letters) and one with nonverbal complex nonmeaningful sounds. Replicating previously observed findings, blind participants outperformed the sighted on both letter span tasks. Blind participants also recalled more letters on the complex letter span task, in which solving intervening equations precluded rehearsal. Critically, the same blind participants showed much larger advantages on the verbal as compared to the nonverbal recognition task. These results suggest that blindness selectively enhances memory for verbal material.

Keywords: Congenitally blind, verbal, nonverbal, memory, recognition memory

Introduction

A distinguishing feature of humans is their ability to adapt to variation in experience. A key illustration comes from studies of sensory loss. People born blind gather information through nonvisual means, including not only audition and touch, but also linguistic communication and social learning. Language in particular, serves as an efficient source of information about phenomena that sighted people observe through vision, such as person identity, spatial layouts, color, fashion, appearance of distal objects, and visual events (Bedny, Koster-Hale, Elli, Yazzolino, & Saxe, 2019; Bigham et al., 2010, October; Burton, Brady, et al., 2012; Kim, Elli, & Bedny, 2019). Some evidence suggests that blindness enhances aspects of linguistic abilities, perhaps as a result of relying heavily on language as a source of information. For example, people born blind show speeded lexical access and outperform the sighted when answering comprehension questions about grammatically complex sentences (Loiotile, Omaki, & Bedny, 2019; Röder, Demuth, Streb, & Rösler, 2003; Röder, Rösler, & Neville, 2000).

Verbal, Nonspatial Memory in Blind over Sighted

A particularly pronounced blindness-related advantage is observed in verbal memory. People who are blind recall longer lists of letters, words, and numbers, both with long (e.g., one week) and short delays (e.g., four seconds) (Occelli, Lacey, Stephens, Merabet, & Sathian, 2017; Pasqualotto, Lam, & Proulx, 2013; Raz, Striem, Pundak, Orlov, & Zohary, 2007; Rokem & Ahissar, 2009; Smits & Mommers, 1976; Stankov & Spilsbury, 1978; Tillman & Bashaw, 1968; Withagen, Kappers, Vervloed, Knoors, & Verhoeven, 2013). Blind individuals remember more items and are also more likely to recall them in the correct order (Pasqualotto et al., 2013; Raz et al., 2007). One study found that people born blind could remember twice as many words as sighted people (Raz et al., 2007).

People who are blind also show superior memory on more complex tasks involving manipulating or updating verbal information, although evidence is somewhat more mixed (e`.g`. Castronovo & Delvenne, 2013; Pigeon & Marin-Lamellet, 2015). Blind adults outperformed the sighted on backward span tasks that required recalling digits in reverse order (Occelli et al., 2017). One study found superior performance on n-back tasks with raised tactile letters at intermediate load levels (Bliss, Kujala, & Hämäläinen, 2004). Blind individuals also recalled lists of consonants in serial order better than sighted participants, even when required to complete an intervening pitch discrimination task prior to recall, though arguably pitch discrimination may provide insufficient interference for a verbal memory task (Dormal, Crollen, Baumans, Lepore, & Collignon, 2016). In another study, blind adults better remembered sentence-final words in an incidental encoding paradigm with 80 sentences (Röder, Rösler, & Neville, 2001). Both studies support the hypothesis that blind individuals' superior working memory abilities may be specific to verbal information. Some evidence suggests that blind individuals' working memory advantage emerges early in development. One study found that 10-year-old blind children outperform sighted children on a listening word span and on backward digit span tasks (Withagen et al., 2013). Blindness-related memory advantages have been documented as early as six years of age (Hull & Mason, 1995). Together, these studies demonstrate improved verbal memory among people who are blind over the sighted across a range of tasks.

A key outstanding question is whether blindness enhances verbal memory in particular or memory more generally. Blindness arguably enhances demand for remembering many types of information, including spatial routes in the absence of visual landmarks, voices in the absence of facial features, and object sounds' locations in the absence of access to distal objects' colors and shapes (Föcker, Best, Hölig, & Röder, 2012; Fortin et al., 2008; Voss et al., 2004). One possibility is that people who are blind demonstrate improved memory for all these varied types of information, including spatial layouts, sounds, and smells. On the other hand, blindness could selectively improve verbal memory. As noted above, language may serve as a particularly efficient source of information about varied contents and be an effective tool for encoding and maintaining information. Studies with other expert populations suggest that memory for different information types often improves independently. For example, simultaneous translators show superior working memory for linguistic material, and expert chess players show superior memory for chess configurations (Chase, 1973; Christoffels, De Groot, & Kroll, 2006; for review, see Ericsson & Lehmann, 1996). Therefore, verbal memory in people who are blind might selectively improve.

Nonverbal Memory in Blind and Sighted

Few studies have directly compared the same blind and sighted adults' verbal and nonverbal memory performance. Studies that have compared blind and sighted adults' nonverbal memory performance alone find mixed results. A handful of studies find superior memory among blind individuals for meaningful, verbalizable sounds, such as the sound of a clock ticking, turning a book's pages, and linoleum floor squeaks (Cornell Kärnekull, Arshamian, Nilsson, & Larsson, 2016). These advantages persist, even when participants complete intervening tasks involving generating words beginning with a certain letter and discriminating nonverbal pitches (Cornell Kärnekull et al., 2016; Röder et al., 2003). Interestingly, the advantage among people born blind was more pronounced with a semantic (naming the sound) as compared to a physical encoding strategy (stating the noises' volume Röder & Rösler, 2003). To that end, verbalizing the sounds may mediate the blindness related advantage observed for meaningful sounds.

Consistent with the idea that blindness related advantages are restricted to verbal or verbalizable material, a number of studies with non-verbalizable materials have failed to find blindness-related advantages. For example, one study found no blindness advantage when participants listened to verbal stimuli but remembered nonverbal information. In this study, blind and sighted individuals performed with equal accuracy when listening to a pseudoword and making n-back judgments on the speaker's identity (as specified by the voice; Gudi-Mindermann et al., 2018). While some studies do find superior memory for voices and tones among people born blind, the findings are inconsistent (Bull, Rathborn, & Clifford, 1983; but see Stankov & Spilsbury, 1978). Several studies with spatial tactile tasks similarly find no advantage among people who are blind. In one recent study, sighted and blind participants equally recalled haptically encoded target cubes' locations on a 2D matrix (Occelli et al., 2017). Crucially, the same group of blind participants outperformed the sighted on two verbal memory tasks, including a backwards digit span task and a word list recall task (Occelli et al., 2017). This study thus provides strong evidence for the hypothesis that blind participants who show verbal memory advantages do not show spatial memory advantages. Converging evidence comes from spatial memory navigation tasks and an adaptive tactile n-back task (Cornoldi, Cortesi, & Preti, 1991; Gudi-Mindermann et al., 2018; for a review, see Struiksma, Noordzij, & Postma, 2009).

In summary, prior evidence suggests blind individuals have superior verbal memory as compared to the sighted (Occelli et al., 2017; Raz et al., 2007). By contrast, studies using non-verbalizable stimuli find mixed results (Gudi-Mindermann et al., 2018; Sinclair, Dixit, & Burton, 2011).

Motivating the Study

The available evidence suggests that blind individuals may exhibit a specific verbal memory advantage. However, while suggestive, the evidence falls short of distinguishing between the verbal memory and general memory advantage hypotheses. As noted above, previous studies show some blindness-related memory advantages for nonverbal meaningful sounds (Cornell Kärnekull et al., 2016). These advantages may be related to verbalizability, yet whether this is the case is unknown. Evidence from spatial tasks is complicated to interpret with respect to the verbal memory hypothesis since prior evidence suggests blind and sighted individuals' performance differs on some spatial reasoning tasks. For example, sighted individuals outperformed blind participants in a mental imagery task using verbal cues (e.g. "left" or "right") to mentally navigate through a previously explored 3D matrix of cubes (for a review, see Cattaneo et al., 2008; Cornoldi et al., 1991). On a spatial imagery task, congenitally blind and sighted participants followed an imaginary pathway through either two or 3D matrices of cubes based on verbal instructions while also completing an interfering finger-tapping task on half the trials (Aleman, van Lee, Mantione, Verkoijen, & de Haan, 2001). Blind participants recalled the final cube’s location on the pathway significantly worse than sighted participants, and interference affected both groups equally, with no group by interference interaction. An additional study found that when memorizing target cubes’ locations on two and 3D matrices, following imaginary pathways based on verbal instructions, and identifying the final cube’s location on each pathway, blind participants recalled final locations worse than sighted participants (Vecchi, 1998). Spatial and imagery performance differences between blind and sighted people could mask a nonverbal memory advantage among those born blind.

Critically, no prior study has compared the same blind and sighted participants’ performance on matched verbal and nonverbal tasks. One reason for this is that most verbal memory tasks require generating responses (e.g., reporting a remembered list of words), which is impossible for nonverbal material. To address this question, we used matched verbal and nonverbal recognition memory tasks. Participants heard either a target sequence of letters (5 to 15 letters long) or a sequence of target nonmeaningful complex sounds (3 to 15 sounds long). They then heard a probe sequence and decided whether it was identical to the target sequence. To respond correctly, participants had to remember both the identity and the order of the letters and sounds. Non-match lists were created by either interchanging two items’ positions, replacing one item with another, or moving an item two or more positions). To ensure that any differences between verbal and nonverbal tasks were not related to difficulty alone, we manipulated load to match the verbal (with letters) and nonverbal (with sounds) recognition memory tasks on difficulty.

To compare the current results to prior literature, we also tested the same blind and sighted participants on forward and backward letter span tasks. Finally, we used a complex span task to determine whether blindness-related advantages would persist even with difficult interfering verbal material. One possibility is that blindness-related verbal memory advantages are only observed in tasks allowing rehearsal of verbal material, perhaps because of more efficient rehearsal strategies. Previous studies have only used nonverbal interfering materials (i.e. tones) or linguistic interfering material, which blind people may process more easily (Cornell Kärnekull et al., 2016; Lane, Kanjlia, Omaki, & Bedny, 2015). In the current study, participants completed a complex span task, which required them to remember letter sequences while judging the validity of interfering math equations.

Methods

Participants

Twenty participants who are congenitally blind (13 female) and 22 age and education matched sighted controls (14 female) took part in the study (see Table 1 for demographic details). One sighted participant only took part in recognition tasks. Three participants who are blind did not perform the Woodcock Johnson III (WJIII) standardized tests.

All participants were native English speakers, except one sighted participant who learned English at age five. We collected data from participants who are blind at three separate national conventions of the National Federation of the Blind (2014, 2016, and 2018). Sighted participants were tested at Johns Hopkins University. Participants who are blind had minimal-to-no light perception from birth due to pathologies in or anterior to the optic chiasm (see Table 1 for list of etiologies). All participants reported no cognitive or neurological disabilities and scored within two standard deviations of their own group on every WJIII task (max z-score within each group: sighted = 1.4, max blind = 2.02).

The study was approved by the Johns Hopkins University Institutional Review Board. All participants provided written informed consent and were compensated for their time at $30 per hour.

Procedures

Participants completed the experimental tasks in the following order: simple verbal forward and backward letter spans (together Experiment 1); complex span (Experiment 2); and nonverbal recognition and verbal recognition (together Experiment 3). WJIII scores were obtained either after all of the experimental tasks or in a separate session. Data were collected as part of a larger testing session.

A female native English speaker recorded all verbal materials. Auditory stimuli were delivered over Audio-Technica headphones. All tasks were administered using a PC laptop running MATLAB (Mathworks, Inc.) and Psychtoolbox (Brainard, 1997; Pelli, 1997). Participant responses were recorded using a button box (Cedrus, RB-730).

Experiment 1: Recall in simple verbal forward and backward letter spans

The forward and backward span tasks were adapted from the Weschler Adult Intelligence Scale

(WAIS) digit span tasks. Digits 1-9 were mapped to letters A-I. On each trial, participants heard a list of letters at a rate of one letter per second. After hearing the final letter, participants were asked to repeat the list back to the experimenter in the exact order (forward) or the reverse order (backward). All participants in both groups heard the same lists of letters presented in the same order. Participants heard two trials per span with span length increasing from two to nine for forward span and two to eight for backward span. Accuracy was scored as the proportion of letters recalled in the correct position. The task self-terminated after the participant responded incorrectly on two consecutive trials of a given span, and all subsequent trials were scored as "incorrect" (performance was set to 0).

Experiment 2: Recall in complex verbal letter span task

The complex verbal span task was similar to the letter span task described above. However, an interfering math equation was inserted after each letter within the lists. Participants were thus required to do two tasks at once: remember the letter sequence and judge the validity of math equations. The intervening math equations were intended to preclude participants from rehearsing the letters.

Equations and letter sequences consisted of the following. Math equations were comprised of multiplying or dividing two digits followed by either adding or subtracting a third digit. All incorrect answers were selected to be within 3 digits of the correct answer to discourage reliance on estimation techniques. Letter lists were constructed from 13 letters (A-M). For each list, letters were chosen pseudo-randomly, allowing only for non-consecutive repetitions of one letter at most twice per trial. All participants in both groups heard the same lists of letters and equations presented in the same order.

The event order within each trial was as follows: Participants first heard an equation and a proposed solution (“5 x 3 + 8 = 23,” 5000 ms). Participants decided whether the solution was correct or incorrect. They pressed one of two buttons (first or second from left to right, respectively) to respond. Following the equation and a 300 ms pause, participants heard a to-be remembered letter (500 ms). The pattern of equations and letters continued until the final letter was reached. Participants then heard a tone indicating the end of the trial (75 ms). Following the tone, participants repeated the full list of letters back to the experimenter in the presented order.

Because math abilities can differ substantially within and across groups, participants had an individualized amount of time to respond to the interfering math equations (blind range - 1 to 25 s, sighted range – 0.9 to 18 s). To calculate a participant specific equation time, participants performed 15 practice equations prior to the task. On experimental trials, they were given the mean practice equation response time + 2.5 times the standard deviation of the practice equation response time.

Participants completed three trials per span, with span length increasing from two to 10. Trial accuracy was scored as the proportion of letters recalled in the correct position. Accuracy was averaged across trials and spans to compute an overall score. The task self-terminated if participants recalled 50% or less of letter positions correctly across trials on a span. Because the highest span any participant reached was nine, only spans two through nine were analyzed for each participant.

Experiment 3: Nonverbal and Verbal Recognition tasks

Nonverbal Recognition.

Participants identified whether two lists of nonverbal sounds were matching or non-matching. The lists were comprised of a combination of 13 nonverbal sounds (500 ms), followed by a 400 ms delay. Sounds are posted on osf.io. The nonverbal sounds were created using Audacity (https://www.audacityteam.org/). Across the 13 sounds, dominant frequencies ranged from 172 to 20,155 hZ, and root mean squared amplitude ranged from 9.54 to 93.21 dB. The sounds were chosen so as to minimize similarity to real sound categories (e.g., barking, sneezing, rain) and thus to minimize verbalizability.

The event order within each trial was as follows. Participants heard a target list of sounds (500 ms per sound with a 400 ms delay between sounds), followed by a 1500 ms delay and a probe list of sounds. Participants then indicated whether the target and probe lists were identical by pressing the first (match) or the second (non-match) buttons. Participants could respond at any time while listening to the probe list, and they could also pause the task after completing a trial. (Trial timed out after 1000 s). After the current trial's list finished playing and a response was received, a verbal cue of “Next Trial” indicated the beginning of the following trial.

Each span length contained four match and four non-match trials. On non-match trials, the probe lists could differ from the target lists in three possible ways: one item was replaced with a new one (“identity change”), two items interchanged positions (“swap two”), or one item shifted two or more positions (“slide one over”), causing subsequent items between the new and old positions to shift as well.

Span lengths ranged from 3 to 15, with 8 trials per span length. Accuracy on each trial was scored as correct (1) or incorrect (0). Following the eight trials within a span, the participant’s overall score on the span was calculated. If the participant performed at or below chance (0.50), the task terminated. Performance on the last completed span and on subsequent spans was set to chance.

Verbal recognition.

The verbal forward recognition task was structured and scored similarly to the nonverbal forward recognition task, except lists of letters were presented as opposed to lists of nonverbal sounds. Similar to the complex span, lists of letters were comprised of 13 possible letters (A-M). For each list, letters were chosen randomly, allowing for non-consecutive repetitions of a single letter at most twice per trial. The lists were screened to ensure they did not coincidentally spell out a word. Span lengths ranged from 5 to 15.

Woodcock-Johnson III (Control)

Five subtests of the *Woodcock-Johnson III (*WJIII) were administered: (Word Identification, Word Attack, Synonyms, Antonyms, and Analogies). Blind participants used a Braille version of the WJIII. On Word Identification, participants read and correctly pronounced 60 English words (e.g. “bouquet”). On Word Attack, participants read and pronounced 32 non-words (e.g.

“paraphonity”). On Oral-Vocabulary Synonyms, participants read 12 words and provided a synonym for each (e.g. “wild” → “untamed”). On Oral-Vocabulary Antonyms, participants read 12 words and provided an antonym for each (e.g. “authentic” → “fake”). On Oral-Vocabulary Analogies, participants generated words to complete 12 unfinished analogies (e.g. “Wrist is to shoulder, as ankle is to…” → “hip”). Items on each section were increasingly more difficult. Participants had no time limit and were given no feedback. Participants were allowed to skip any questions but could not return to them. Section accuracy was scored as the percent correct on all possible items in that section. Skipped trials were scored as incorrect.

Participant	Gender	Age	Cause of blindness	Light perception	Years of Education
CB_01	F	34	Leber's Congenital Amaurosis	None	17
CB_02	M	38	Leber's Congenital Amaurosis	None	19
CB_04	F	34	Leber's Congenital Amaurosis	Minimal	17
CB_05	F	19	Leber's Congenital Amaurosis	Minimal	15
CB_07	F	35	Anopthalmia	None	19
CB_08	M	40	Bilateral amnothalmia	None	17
CB_09	F	38	Micro-opthalmia	None	16
CB_10	F	22	Leber's Congenital Amaurosis	Minimal	19
CB_13	F	19	Optic Nerve Displacia	None	13
CB_14	F	28	Leber's Congenital Amaurosis	None	16
CB_15	F	18	Leber's Congenital Amaurosis	Minimal	13
CB_16	M	19	Glaucoma	None	12
CB_18	M	24	Retinopathy of Prematurity	Minimal	13
CB_19	M	61	Congenital glaucoma	Minimal	17
CB_20	F	21	Fraser’s syndrome	None	16
CB_21	F	25	Bilateral amnothalmia	None	17
CB_22	M	38	Leber's Congenital Amaurosis	None	17
CB_23	F	24	Leber's Congenital Amaurosis	Minimal	16

CB_24	F	48	Septo-optic Dysphasia	None	17
CB_25	M	18	Leber's Congenital Amaurosis	Minimal	13
Average					
Blind (N=20)	13F	30.26	-	-	15.95
Sighted (N=22)	14F	32.86	-	-	16.64

Table 1: Participants demographic information.

Group	Word ID	Word Attack	Synonyms	Antonyms	Analogies
Blind	96% (4)	92% (6)	89% (12)	79% (15)	68% (16)
Sighted	95% (4)	92% (0.6)	82% (14)	78% (16)	71% (15)

Table 2: Average Woodcock-Johnson III Scores per group. Group means and standard deviations for task performance.

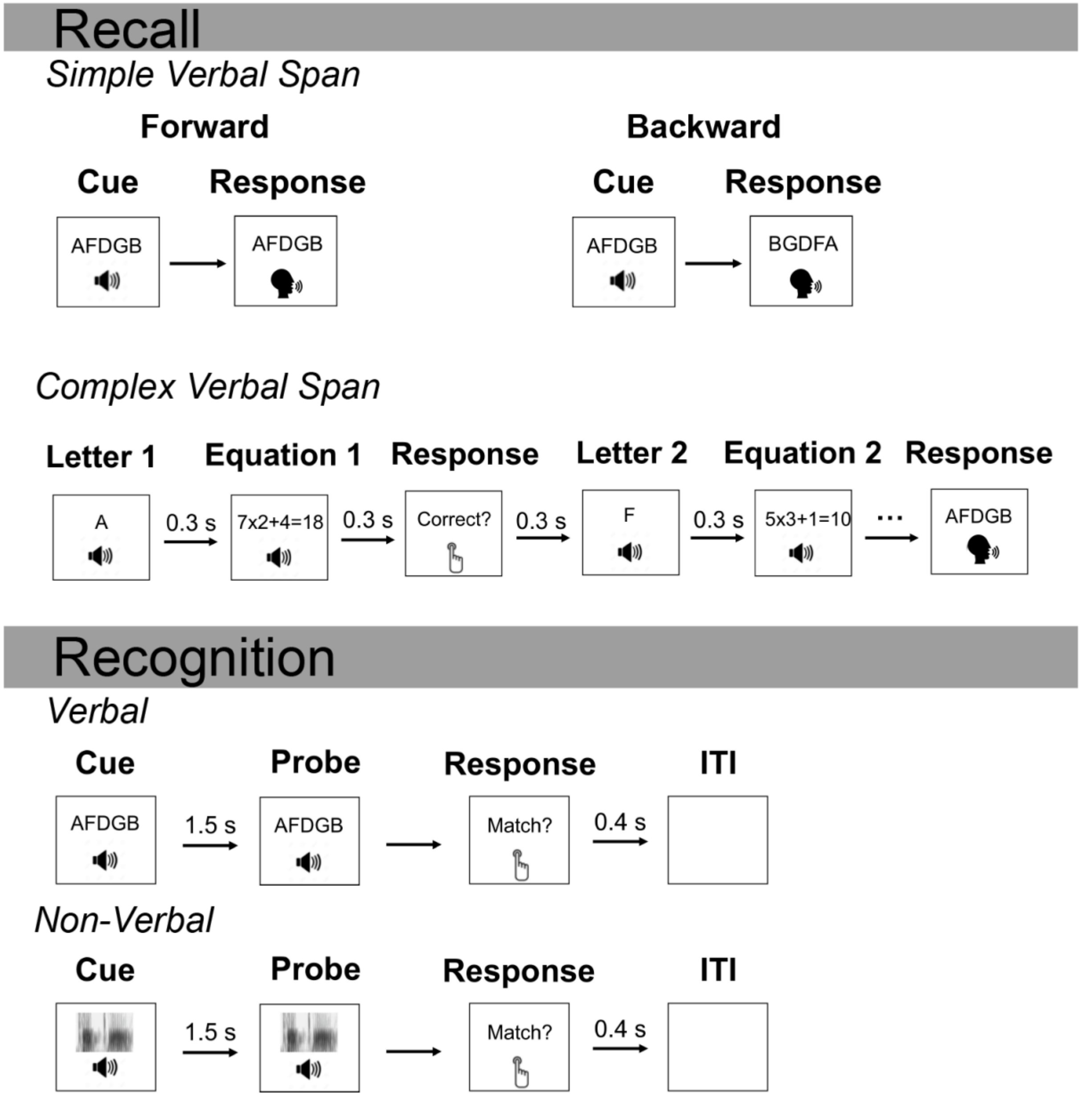

Figure 1: Tasks Recall: Participants repeated sequences of letters presented to them in an audio format. For forward recall, participants repeated the list in the same order as presented but for backward recall, in the opposite order as presented. During complex recall, participants determined the correctness of a math equation followed by hearing each letter to be remembered.

Recognition: Participants were given two lists and determined if they matched. For the verbal task, the lists consisted of letters. For the nonverbal task, the list consisted of nonverbal sounds.

Data Analysis

Recall: Forward, Backward, and Complex

Accuracy per trial was calculated as the proportion of letters recalled in their correct position in the cue list. Accuracy per load was calculated by averaging accuracy across each load's two trials. If a participant was not tested on a load (e.g. load 8) because of poor performance on prior loads (e.g. 6 and 7), performance on that load (i.e. load 8) was set at chance. The task used a self-determination procedure. If a participant's overall span performance was at or below chance (0), the task terminated. Performance on all subsequent spans was marked as "incorrect" (performance set at chance, 0).

A subset of participants who were blind (n=8) completed all trials regardless of performance, i.e., the task continued after two incorrect responses. However, in order to combine their data with that of the previous cohort's, they were scored in the same way. All trials occurring after two consecutive errors were scored as "incorrect".

Recognition: Verbal and Nonverbal

Accuracy per load was averaged across the load's eight trials. If a participant was not tested on a load due to poor performance on prior loads, then performance was set at chance and d' was set to 0 for that load. If a participant completed a load but performance was below chance, then performance was also set at chance and d' set at 0 in order to equate with those participants that were not tested on that particular load due to poor performance on prior loads. For the nonverbal task, only loads 3 to 6 were analyzed. During piloting, these loads were found to produce similar performance as loads 5 to 8 in the verbal task.

Results

Experiment 1: Recall in simple verbal span task, forward and backward

Individuals who are blind showed enhanced short-term memory recall in a simple verbal span task. In a group (blind vs. sighted) by direction (forward vs. backward) by load (2 through 9 spans) 2 x 2 x 8 ANOVA (Fig 2a), participants who are blind performed overall better than the sighted across spans for both forward and backward recall (main effect of group, $F(1,39) = 8.25$, $p < .001$). Both groups performed worse with increasing load (main effect of load, $F(7, 273) = 210.86$, $p < .001$), with load effects more pronounced in the backward than forward recall task (direction X load interaction, $F(7, 273) = 30.72$, $p < .001$). Notably, increasing load affected individuals who are blind less (group X load interaction, $F(7, 273) = 3.62$, $p < .001$). By contrast, direction equally affected both participant groups (directionality X group interaction, $F(1,39) = 0.36$, $p = .548$), both groups performing more poorly on the backwards than forwards span task (directionality effect, $F(1, 273) = 76.09$, $p < .001$).

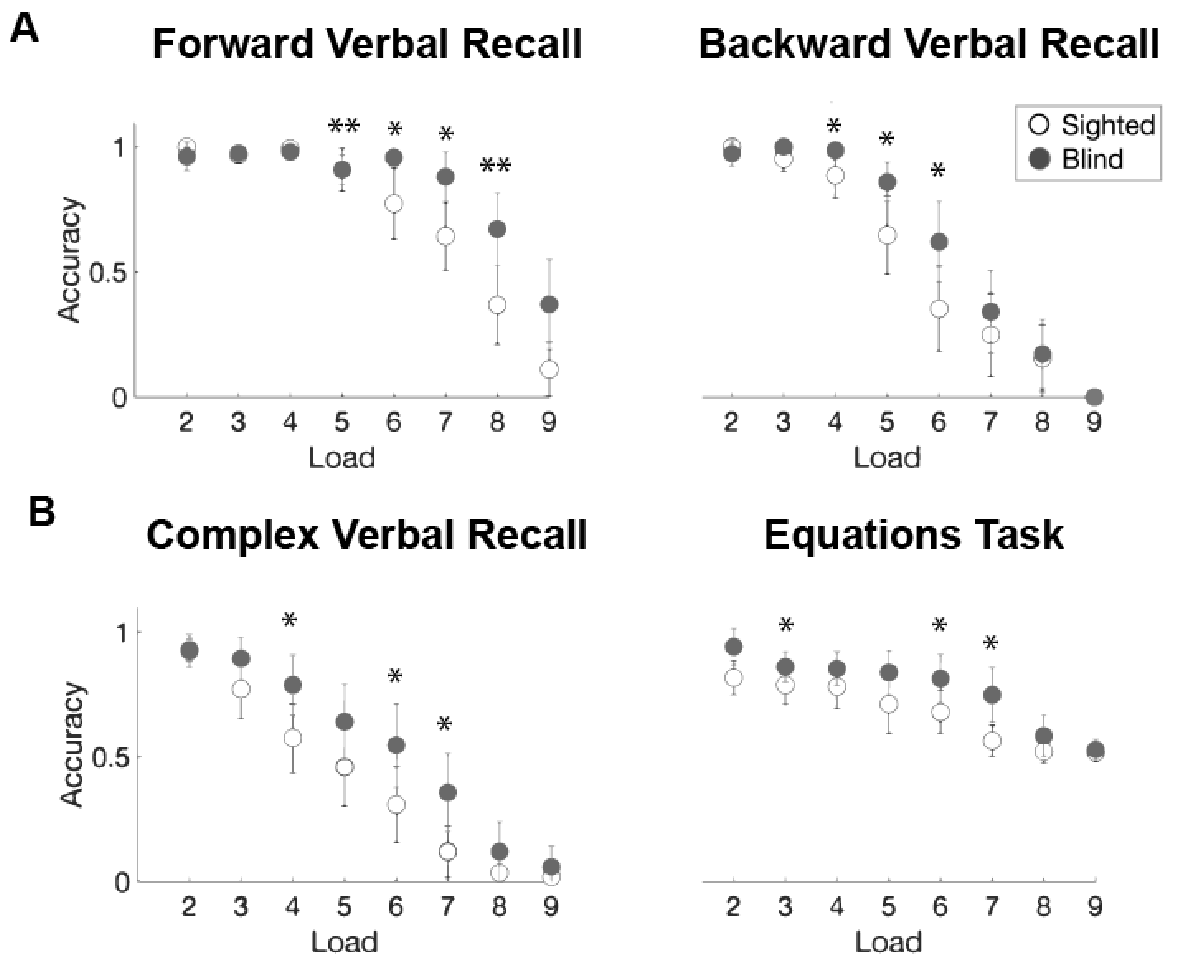

Figure 2: Verbal Recall Performance

Performance on recall tasks. A) Average recall accuracy per load for simple verbal forward and backward span tasks. B) Average recall accuracy per load for the complex verbal span task and the equations task. Error bars indicate 95% confidence intervals. The black stars indicate significance: * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

Experiment 2: Recall in complex verbal span task

Individuals who are blind continued to show enhanced short-term memory recall despite interference (with math equations) on a complex span task. In a 2 x 8 group by load ANOVA, main effects of group, load, and task (letter recall and equation judgment) on accuracy were found (Fig 2b; group, $F(1,39) = 6.55$, $p < .01$; load, $F(7, 273) = 104.86$, $p < .001$; task, $F(1,39) = 26.70$, $p <.001$), but not a group by load interaction effect ($F(7, 273) = 1.93$, $p = .065$, Figure 2).

Participants who are blind also outperformed the sighted on the equations interference task. Their superior accuracy at recalling letters was not driven by a tradeoff with the equations task. In fact, participants who are blind performed significantly better than the sighted on the equations task across loads (Fig 2b; 2 x 8 group-by-load ANOVA group, $F(1, 39) = 6.610$, $p < .05$). Increasing load in the concurrent letter-working memory task negatively impacted both groups' performance on the equations task (load, $F(7, 273) = 67.13$, $p < .001$).

Experiment 3: Verbal and nonverbal recognition task

D' was used as an outcome measure for the recognition memory task to account for any potential differences across groups in bias. Note that all results are similar when raw accuracy data was analyzed instead of D'. Individuals who are blind only showed enhanced recognition memory with verbal material. A group (blind vs. sighted) by load (4 loads) by task (verbal vs. nonverbal) 2 x 4 x 2 ANOVA revealed main effects of all 3 factors. Participants who are blind overall outperformed the sighted (Fig 3a; main effect of group, $F(1,40) = 16.20$, $p < .001$). Performance decreased with increasing load, ($F(3, 120) = 106.76$, $p < .001$). Participants did not perform better on the verbal than on the nonverbal task, $F(1,40) = 3.391$, $p = .055$). The main effect of group was qualified by a group by task interaction, such that the difference between blind and sighted groups was more pronounced in the verbal than nonverbal task, ($F(1,40) = 3.82$, $p < .05$). Furthermore, in the nonverbal recognition task, a single load drove the effect of group, whereas all loads showed an effect of group in the verbal task. We also found a task by load interaction, such that the effect of load was more pronounced in the nonverbal task (task X load, $F(3, 120) = 7.16$, $p < .001$).

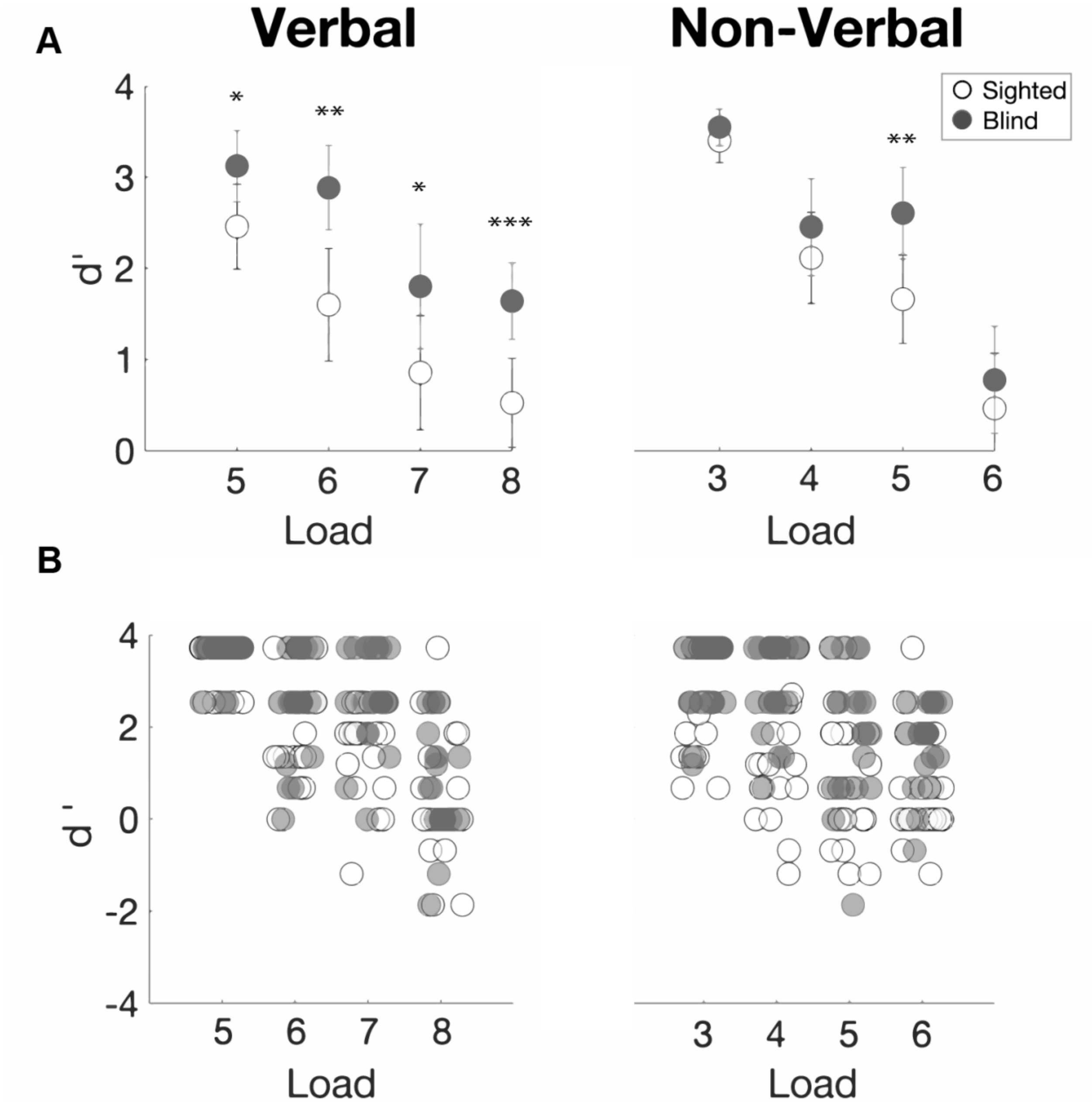

Figure 3: Recognition Performance

Performance on recognition tasks. A) Average d’ per load for each group is shown for verbal and nonverbal tasks. B) Individual subjects’ d’. Markers are jittered for visualization purposes. Error bars indicate 95% confidence intervals. The black stars indicate significance: * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

Discussion

We report that congenital blindness is associated with a selective advantage for verbal as compared to nonverbal memory. Replicating and extending prior results, we show that adults who are blind from birth outperform the sighted on verbal recall tasks, being better able to recall letters, words, and digits in the correct order on forward, backward, and complex span tasks (Cohen, Voss, Lepore, & Scherzer, 2010; Hull & Mason, 1995; Occelli et al., 2017; Raz et al., 2007; Rokem & Ahissar, 2009; Swanson & Luxenberg, 2009; Withagen et al., 2013). We further find that blindness-related advantages extend to verbal recognition memory. Participants who are blind were better at distinguishing between previously heard lists of letters and lists containing foil letters. Although both blind and sighted participants made more errors with increasing list lengths, on average people born blind recognized more letters correctly (approximately 10% more). On average, those born blind also remembered more letters both in forward and reverse order, and when simultaneously judging the validity of interfering math equations. Crucially, we observed a group-by-verbal material interaction, such that blindness related advantages were more pronounced for verbal as compared to nonverbal recognition memory. Blind participants significantly outperformed the sighted on all loads of the verbal recognition task. No group difference emerged on the nonverbal recognition task except at one load level, and this effect was nonsignificant when collapsing across loads. These results support the hypothesis that blindness promotes enhanced memory specifically for verbal material.

Higher verbal over nonverbal memory

The larger verbal memory advantages currently observed among people born blind is consistent with a number of prior studies. One study reported that blind participants outperformed sighted ones on verbal but not spatial memory tasks (Occelli et al., 2017). Specifically, blind participants outperformed sighted ones on a backward digit span task and on short and long-term word list recall tasks, while no differences were found on a haptic spatial corsi-block task in the same blind and sighted participants. The present findings show that blind individuals exhibit a verbal versus nonverbal memory dissociation even when using a nonverbal, nonspatial task for comparison, thus extending previous results. The current results are also consistent with evidence that congenitally blind individuals' higher performance using nonverbal sounds or tactile stimuli appears to be related to verbalizability. Prior studies find blind individuals recognize more verbalizable sounds (e.g., musical instruments or turning book pages) than sighted participants (Cornell Kärnekull et al., 2016; Röder & Rösler, 2003). In contrast, with non-verbalizable stimuli, blindness related advantages are absent in the current study and in other work (e`.g`. n-back tasks matching vibrations and voices Burton, Sinclair, & Dixit, 2010; Gudi-Mindermann, 2018 #41 and a recognition memory task using vibrotactile rhythms Sinclair et al., 2011). Therefore, existing evidence specifically supports the verbal memory advantage hypothesis.

Role of Rehearsal

Why do blind individuals outperform the sighted specifically on verbal memory tasks? One possibility is that blind individuals have better rehearsal strategies specifically for verbal material. We cannot fully rule out this hypothesis, but it seems unlikely based on the available evidence. In the current study, blind participants' advantage is evident on both simple and complex span tasks with intervening equations. That is, blind participants continued to recall more letters in the correct order while solving a math equation between each letter presentation. Prior studies also find blindness related memory advantages in the context of interference. As compared to sighted individuals, blind participants recall more letters and verbalizable sounds after completing an intervening pitch discrimination task (Dormal et al., 2016; Röder et al., 2003). On a long-term memory task, blind participants recognized more verbalizable sounds than sighted participants after generating words beginning with a certain letter over 8-9 minutes (Cornell Kärnekull et al., 2016). Similarly, blind children recalled more sentence-final words than sighted children while judging the same sentences as true or false during a listening span task (Withagen et al., 2013). One study even found better memory on an incidental memory paradigm, where blind participants recognized more previously heard sentence-final words as compared to sighted participants after judging the same sentences as meaningful in an intervening task (Röder et al., 2001). Together with the present evidence, these studies suggest memory advantages in blindness are likely unrelated to more efficient rehearsal strategies for verbal information per se.

Rather, we hypothesize blind individuals' verbal memory advantages reflect a rehearsal-independent improvement in verbal memory observed for a range of verbal and verbalizable material, from letters to numbers and words. As noted in the introduction, blind individuals rely heavily on language to gain information that is available to sighted people through vision (Bedny et al., 2019; Kim et al., 2019). Previous studies find that people born blind show improved behavioral abilities on some non-memory related language tasks (Loiotile et al., 2019; Röder et al., 2003; Röder et al., 2000). One possibility is that verbal memory improvements in blindness are an example of improved language skills. A related possibility is that people born blind improve their verbal memory because language is so heavily relied upon as an information source. In other words, since blind individuals rely heavily on language to learn about their surroundings, they also rely on verbal memory to retain the relevant information. Finally, language may provide a particularly efficient means of encoding and maintaining information. If so, improving verbal memory may be the most efficient means of improving memory for the widest array of behaviorally relevant information. In this regard, language might serve as a mental tool, both for gathering and retaining information (for related argument, see Frank, Everett, Fedorenko, & Gibson, 2008).

‘Visual’ Cortex Plasticity and Verbal Memory

An intriguing question to be addressed in future work is whether enhanced verbal memory in blindness is related to plasticity in classic fronto-parietal and medial temporal memory systems or ‘visual’ cortex plasticity (e`.g`. Amedi, Raz, Pianka, Malach, & Zohary, 2003; Osaka et al., 2003; Rypma & D’Esposito, 1999). People who are blind activate ‘visual’ cortices when retrieving words from long-term memory, and the degree of activation in ‘visual’ cortex during recognition is correlated with memory performance (Raz, Amedi, & Zohary, 2005). Moreover, across blind individuals, people with larger ‘visual’ cortex responses to linguistic stimuli show better verbal memory performance (Amedi et al., 2003; Burton, Sinclair, & Agato, 2012).

Blind individuals also recruit 'visual' occipital cortices during a range of language tasks, including listening to sentences and short stories, as well as reading braille (Bedny, Pascual-Leone, Dodell-Feder, Fedorenko, & Saxe, 2011; Burton et al., 2002; Crollen et al., 2019; Röder, Stock, Bien, Neville, & Rösler, 2002).

Whether visual cortices participate in nonverbal memory in blindness is less clear. One study found larger responses to 2-back than 0-back tasks in occipital cortices with nonverbal sounds, sound locations as well as words (Park et al., 2011). However, a study using a vibro-tactile 1-back task failed to find occipital responses in blindness (Burton et al., 2010). Similarly, in another study using vibrotactile rhythms, occipital cortex activity did not predict recognition accuracy in blind or sighted participants (Sinclair et al., 2011). None of these studies manipulated load parametrically, making interpretation of these findings complex. Two recent studies found that in blind but not sighted participants, nonverbal memory training incorporated occipital areas into working memory networks, although no occipital responses were observed prior to training (Gudi-Mindermann et al., 2018; Rimmele, Gudi-Mindermann, Nolte, Röder, & Engel, 2019). Neither of these studies observed nonverbal memory advantages in the blind group either before or after training. In general, occipital activation on a task in blindness is not always associated with behavioral benefits (e`.g`. Kanjlia, Lane, Feigenson, & Bedny, 2016; Kanjlia, Loiotile, Harhen, & Bedny, 2021). Whether verbal memory advantages are related to visual cortex plasticity in blindness remains to be tested in future research.

Conclusion

In sum, we find that people who are born blind show larger memory advantages for verbal than nonverbal material. These advantages are observed for both complex and simple span tasks, as well as for recognition memory tasks. Specific verbal memory enhancements may reflect either language's importance as an information source when lacking vision or its efficiency as a tool for committing information to short and long-term memory.

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