Perks of blindness: Enhanced verbal memory span in blind over sighted adults

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ABSTRACT

Blind individuals commonly use verbal encoding (i.e. text-to-speech) and memory-based strategies (i.e. serial recall) for situations in which sighted individuals use vision (i.e. finding items). These strategies may serve to train cognitive systems responsible for maintaining and manipulating verbal information. To test this hypothesis, we investigate whether early visual deprivation is linked to improved verbal short-term and working memory abilities, and thus might illustrate experience-dependent plasticity in memory systems. We also test whether the sensory modality for encoding information influences performance. Our data show that blind adults recalled more items on a verbal short-term memory span task than sighted participants. Furthermore, blind individuals performed equally well on auditory forward and backward conditions despite the fact that recalling items in reverse order is more difficult for the general population. However, the benefits of recalling items in reverse order did not extend to the tactile domain, specifically, a braille version of the short-term memory digit span task in blind individuals. Furthermore, we observed no differences between blind and sighted individuals on a more demanding auditory n-back task evaluating more complex working memory processes. We conclude that the memory benefits associated with blindness might be restricted to auditory-verbal short-term memory and likely reflect strategy use and practice.

1. Introduction

Individuals who are blind must rely extensively on nonvisual memory strategies to complete everyday tasks that sighted individuals typically accomplish visually. When navigating, individuals who are blind utilize their working memory to orient using auditory cues while, for example, maintaining conversation (Raz et al., 2007). Those who are blind also rely on memory for serial order and position to distinguish items that otherwise can only be distinguished visually (e.g., different flavored yogurt in identical sealed containers differentiated solely by labels; Raz et al., 2007).

One hypothesis is that blind individuals’ memory reliance may provide unique, practice-related benefits, illustrating experience-dependent plasticity of memory systems. This has been most clearly demonstrated in the verbal short-term memory domain, particularly among congenitally or early blind individuals. For example, children who become blind at birth or early in life recall significantly more items than sighted children, as demonstrated with auditory span tasks (Hull and Mason, 1995; Swanson and Luxenberg, 2009; Withagen et al., 2013). Likewise, adults with congenital or early onset blindness exhibit improved short-term recall for letters, digits, and words (Amedi et al., 2003; Arcos et al., 2022; Occelli et al., 2017; Pasqualotto et al., 2013; Raz et al., 2007; Roder et al., 2001).

A number of factors mediate the observed improved memory span in congenital or early blindness. For example, superior verbal memory spans are not typically reported for individuals that experience late onset blindness or those with residual vision (Cohen et al., 2010; Dormal et al., 2016; Hull and Mason, 1995; Pasqualotto et al., 2013; Smits and Mommers, 1976). Moreover, evidence indicates blind individuals’ enhanced short-term memory is restricted to the auditory-verbal modality for highly salient linguistic input. For example, blind and sighted participants show equivalent performance on recognition memory for nonverbalizable sounds (Arcos et al., 2022), and the improved span performance in congenitally blind participants disappears after accounting for perceptual encoding efficiency differences (Rokem and Ahissar, 2009).

Furthermore, improvements in verbal short-term memory do not extend to spatial short-term memory. Studies report no group
differences on spatial memory tasks that require recalling object configurations and paths (Occhelli et al., 2017; Vecchi et al., 2004), and sighted participants commit fewer errors than blind participants on spatial imagery tasks (Cornoldi et al., 1991). Of note, these latter tasks require maintaining and manipulating objects’ relative spatial positions, thus drawing upon executive processes such as working memory, beyond short-term memory storage demands.

Together these findings are consistent with neurophysiological evidence that congenitally blind individuals’ “visual” cortex is recruited during linguistic tasks, including verbal memory tasks (Amedi et al., 2003; Bedny et al., 2011; Hamilton and Pasqual-Leone, 1998; Pant et al., 2020; Röder et al., 2002; Sadato et al., 1996). Whether this reorganization reflects compensatory mechanisms or inherent pluripotency of capacity of cortex traditionally characterized as unimodal is not yet clear (Savelier and Neville, 2002; Bedny, 2017). Age of visual impairment onset, however, is believed to be a critical variable such that early onset provides dual opportunity for memory training, both through cortical plasticity during a critical developmental window, and as a result of extensively practicing memory strategies daily to promote functional independence.

Whether experience-dependent training and/or plasticity may also enhance other executive systems in early blindness has gained increasing interest. For example, early blind individuals have improved selective attention relative to sighted individuals as evaluated using speeded reaction times (Kujala et al., 1997). The blind also show improved auditory and tactile selective attention, including divided or sustained attention over long intervals (Collignon et al., 2006; Pigeon and Marin-Lamellet, 2015). However, evidence of either impaired or enhanced performance in more complex working memory domains is much less clear, depending on how working memory processes are evaluated. For example, when assessing working memory using a backwards verbal span task, some studies report significantly larger spans in early blind participants versus sighted (Hull and Mason, 1995; Occhelli et al., 2017; Withagen et al., 2013), while others report no group differences (Bathelt et al., 2018; Pigeon and Marin-Lamellet, 2015; Rokem and Ahissar, 2009; Wyver and Markham, 1998). Nonetheless, blind participants consistently outperform sighted ones in working memory studies evaluating verbal span with interference tasks to suppress rehearsal (Arcos et al., 2022; Cohen et al., 2010; Dormal et al., 2016). In early and late blind participants, some studies measuring working memory through n-back tasks report faster reaction times (Pigeon and Marin-Lamellet, 2015, 2017), while still others report no differences in accuracy between the two samples (Park et al., 2011; Pigeon and Marin-Lamellet, 2015).

Each task’s differential loading on key aspects of working memory processes may partly explain these discrepancies. While backward spans rely largely on maintaining and manipulating items, interference tasks require participants to suppress task-unrelated information, and n-back tasks impose even stronger demands on manipulating information (Kane et al., 2007). Verbal short-term and working memory also rely on unique brain systems (as demonstrated in sighted individuals). Verbal storage is associated with the left inferior frontal gyrus and parietal cortex, while executive functions involved in verbal working memory are associated with right dorsolateral prefrontal cortex (Jonides et al., 2008). Blind individuals recruit similar brain regions during verbal working memory, and additionally recruit occipital cortex (Park et al., 2011). Thus experience-dependent plasticity may be more pronounced in brain networks supporting verbal working memory maintenance processes.

Consideration of the sensory modality used to encode experimental information during verbal working memory tasks is important. Sighted adults and children have demonstrated benefits for information encoded in a preferred modality, as evidenced by improved verbal recall for items read visually as compared to auditorily (Frick, 1984). Presumably also, encoding information through non-dominant modalities imposes higher cognitive loads, i.e., increases task difficulty, which may impair subsequent recall (De Jong, 2010). Better recall when visually reading may also reflect observers’ ability to actively explore information visually at a self-guided pace, the tendency for visual information to persist for longer time durations than auditory information, and differences in how readily information can be verbalized, which is faster for visual as compared to auditory information in sighted individuals (Frick, 1984; Klatsky et al., 2006).

Blind individuals’ preferred sensory modality for encoding verbal information is not yet clear. Consistently, blind participants are more efficient when encoding auditory information as compared to the sighted (Hötting and Röder, 2009; Muchnik et al., 1991; Pigeon and Marin-Lamellet, 2017; Rokem and Ahissar, 2009). Early blind individuals also process heard linguistic information more efficiently than sighted individuals (Röder et al., 2003). Moreover, improved linguistic processing may transfer to tactile encoding. Sighted individuals make significantly more errors on verbal working memory n-back tasks when using raised letters versus visual letters, while blind braille readers perform equally well when using raised tactile or braille letters (Bliss et al., 2004). When comparing auditory versus tactile encoding, blind and braille literate children recalled more words encoded in braille as compared to when listening to words (Pring, 1988). This suggests that proficient braille readers may preferentially encode linguistic information in braille.

1.1. Considering socioeconomic status

When measuring executive function, considering an individual’s economic and social opportunities is important. Executive function involves coordinating one’s thoughts and actions to achieve goals (Miller and Wallis, 2009). Low socioeconomic status (SES) is linked to poorer scores on working memory measures (Ursache and Noble, 2016); the disadvantages appear early in development and remain stable through late adolescence, reflecting opportunity gaps. Importantly, those diagnosed with sensory impairments, such as blindness, are more likely to come from low SES backgrounds, in part a consequence of major health inequality (Dandona and Dandona, 2001). This creates the double disadvantage of managing a complex disability in an environment with fewer resources, yet, those who become blind early on have been shown to strengthen their memory abilities and partially compensate for these barriers as a result.

The current study evaluates verbal short-term memory and working memory abilities in participants with and without impaired vision across sensory modalities, while also matching for demographic characteristics to account for potential SES differences. Using three established tasks, we assess the effects of blindness on verbal short-term memory performance (forward digit span), maintaining and manipulating items in verbal working memory (backward digit span), as well as updating and inhibiting verbal items in working memory (n-back).

2. Results

2.1. Digit span

A one-way repeated measures ANOVA with recall order (forward vs. backward) as the within-subjects factor and group (blind vs sighted) as the between-subjects factor revealed a main effect of group on auditory span accuracy ($F(1, 75) = 39.82$, $p < .001$, $\eta^2_p = 0.35$) such that blind participants recalled significantly more items than sighted participants when collapsing across direction (forward and backward; cf. Fig. 1, Table 3, Supplementary Table 2). We found no significant main effect of recall order ($F(1, 75) = 3.02$, $p = .09$, $\eta^2_p = 0.04$) nor a recall order by group interaction ($F(1, 75) = 0.42$, $p = .52$, $\eta^2_p = 0.01$). We also tested whether the item encoding modality (auditory, visual, or tactile) impacted memory span performance. Trials were analyzed separately in the two groups due to the unique modalities in which they participated, i.e., visual and auditory in sighted participants and auditory and tactile in blind participants. Among the sighted
participants, a two-way repeated measures ANOVA revealed a main effect of modality (F(1, 57) = 30.57, \( p < .001, \eta_p^2 = 0.35 \)) such that sighted individuals recalled more items after encoding the list visually rather than when heard. A main effect of recall order was also found (F(1, 57) = 18.46, \( p < .001, \eta_p^2 = 0.25 \)) such that sighted participants recalled significantly more digits in forward as compared to backward order. Sighted participants’ recall order by modality interaction was not significant (F(1, 57) = 1.49, \( p = .23, \eta_p^2 = 0.03 \)).

A two-way repeated measures ANOVA revealed a main effect of modality among the blind participants such that more items were recalled when heard versus read in braille (F(1, 18) = 20.15, \( p < .001, \eta_p^2 = 0.53 \)). Furthermore, we found a main effect of recall order (F(1, 18) = 19.89, \( p < .001, \eta_p^2 = 0.53 \)) such that more items were recalled in forward vs. backward order. However, a significant recall order by modality interaction in blind participants conditioned these main effects (F(1, 17) = 8.46, \( p = .01, \eta_p^2 = 0.32 \)). Post-hoc tests indicated that blind participants recalled the same number of items in reverse and forward order when listening to the lists (t(18) = 0.59, \( p = .56, d = 0.14 \)) and fewer digits in reverse order as compared to forward when reading in braille (t(18) = 8.50, \( p < .001, d = 1.95 \)). Whereas the blind participants did not differ in forward span whether digits were heard or read in braille (t(18) = 0.78, \( p > .05, d = 0.18 \)), backward span performance was significantly better when hearing digits as compared to reading them in braille (t(18) = 6.12, \( p < .001, d = 1.40 \)).

When comparing only blind participants who learned braille before age eight, similar results emerged as compared to the full sample of blind participants. We found a main effect of modality such that more items were recalled when heard versus read in braille (F(1, 15) = 14.73, \( p < .1, \eta_p^2 = 0.495 \)). A main effect of recall order was also found (F(1, 15) = 17.24, \( p = .002, \eta_p^2 = 0.54 \)) such that more items were recalled in forward vs. backward order. However, unlike in the full sample of blind participants, no recall order by modality interaction was found in those literate in braille before age eight (F(1, 15) = 3.83, \( p = .07, \eta_p^2 = 0.20 \)). Among the full sample, self-reported braille proficiency and digit span (forward and backward) were significantly correlated, and this correlation persisted only in the forward span among individuals that learned braille before age eight (Supplementary Table 3).

### 2.3. Groups matched on age and SES

#### 2.3.1. Digit span

In the matched sample, a two-way repeated measures ANOVA on the auditory digit span accuracy scores revealed a main effect of group (F(1, 32) = 30.43, \( p < .001, \eta_p^2 = 0.49 \)), which is consistent with the full sample’s results. We found neither an effect of recall order (forward vs. backward; F(1, 32) = 2.297, \( p = .14, \eta_p^2 = 0.07 \)) nor a group by recall order interaction (F(1, 32) = 0.40, \( p = .53, \eta_p^2 = 0.01 \)). The full correlation relationship between age, SES factors, and the dependent measures is shown in Supplementary Tables 5 and 6.

#### 2.3.2. N-back

Replicating results from the full sample, when matched for age and SES, we found no main effect of group on n-back accuracy (F(1, 32) = 2.10, \( p = .16, \eta_p^2 = 0.06 \)), though the effect size was slightly larger in the matched as compared to the full sample. No group by n-back level interaction was found (F(3, 96) = 0.70, \( p = .56, \eta_p^2 = 0.02 \); cf. Fig. 2).

For RTs, similar to what we observed in the full sample, we found no main effect of group (F(1, 32) = 2.74, \( p = .11, \eta_p^2 = 0.08 \)), and the group by n-back level interaction was not significant either (F(3, 96) = 1.22, \( p = .31, \eta_p^2 = 0.04 \)).

### 2.4. Controlling for stimulus duration

We further considered the possibility that the braille digit span’s extended stimulus duration (1 sec, with a 1 sec ISI) possibly allowed more time for rehearsal and deeper encoding as compared to the rapid, visually presented items (500 msec, with a 1 sec ISI). Therefore, a new

![Fig. 1. Digit span performance as a function of group (accuracy). Performance for sighted individuals is shown on the left (visual and auditory digit spans), and performance for blind individuals is shown on the right (auditory and braille digit spans). Error bars denote +/- 1 standard errors of the mean. Significant differences between forward and backwards span performance (within-subjects) are indicated by asterisks (\( p < .01 \); *** \( p < .001 \)).](image1)

![Table 3](image2)

| Level | Sighted (N=17) | Blind (N=17) |
|-------|----------------|-------------|
| 1-back | 1.00           | 0.75        |
| 2-back | 0.75           | 0.55        |
| 3-back | 0.50           | 0.35        |
| 4-back | 0.25           | 0.15        |

![Fig. 2. N-back performance as a function of level and group (matched participants only). Accuracy reflects PR scores (proportion hits – proportion false alarms). Error bars denote +/- 1 standard errors of the mean.](image3)
group of sighted participants completed the visual digit span using both the standard (500 msec) and an extended (1 sec) stimulus duration, with the extended duration matching the braille presentation time. Participants completed both conditions in randomized order.

A one-way repeated measures ANOVA using digit duration (fast vs. slow) as the within-subjects factor revealed a main effect of digit duration \( F(1, 48) = 26.88, p < .001, \eta_p^2 = 0.53 \) such that the sighted participants performed better on the shorter duration forward trials \( (M = 11.80, SD = 3.46) \) as compared to the longer duration forward trials \( (M = 8.60, SD = 4.38) \). The sighted participants also performed better on the shorter duration backward trials \( (M = 9.00, SD = 2.96) \) as compared to the longer duration backward trials \( (M = 7.64, SD = 3.52) \).

3. Discussion

This study evaluates how visual deprivation may impact verbal short-term and working memory abilities using carefully controlled environments and matching based on participant demographics. We considered preferred sensory modalities during encoding and individuals’ SES. Consistent with previous studies \( (\text{Occelli et al., 2017; Raz et al., 2007; Withagen et al., 2013}) \), we find blind participants have a clear advantage over sighted individuals on a verbal digit span task \( (\text{Occelli et al., 2017; Raz et al., 2007; Withagen et al., 2013}) \). Gains were most evident on the auditory forward span task which drove the group effect. However, differences were also apparent on the backward auditory span task in that reversing digit order did not impact blind individuals’ number of trials correct despite the additional cognitive load. On the braille span task, digit order impacted recall: Backward recall was attenuated as compared to forward recall, consistent with sighted individuals’ lower backward recall on the visual task due to added load effects. We found no evidence of enhanced verbal working memory on an auditory n-back task, even after controlling for age and SES.

3.1. Digit span

Our finding that adults who are blind outperform the sighted on verbal span tasks replicates many previous studies showing congenitally blind populations recall more items as compared to sighted populations \( (\text{Amedi et al., 2003; Hull and Mason, 1995; Occelli et al., 2017; Pasqualotto et al., 2013; Röder et al., 2001; Swanson and Luxenberg, 2009; Withagen et al., 2013}) \). Our findings are consistent with the proposal that the blind’s improved verbal short-term memory is likely a consequence of relying on verbal encoding strategies as an extensive form of training in ecological settings.

We know, for example, that superior verbal short-term memory extends beyond item memory to include serial position recall \( (\text{Raz et al., 2007}) \). Thus, performance on memory span tasks may reflect the use of strategies that explicitly capitalize on ordinal processing, such as chaining, in which adjacent items are associated based on their spatial positions or on timing intervals between items. Sighted individuals trained to use chaining have increased recall on both short-term and working memory tasks relative to non-trained controls, and those with higher memory capacity benefit more from memory strategies as compared to those with lower memory capacity \( (\text{McNamara and Scott, 2001}) \). Whether our results, and those of previous studies, reflect increased verbal memory capacity or increased capacity facilitated through chaining and ordinal positions is unclear.

Our findings may also reflect improved speech processing efficiency. This improvement may, in turn, make available more cognitive resources for engaging short-term memory functions. Studies suggest blind individuals may be more sensitive to speech sounds and selectively attend to targeted speech more effectively \( (\text{Hötting and Röder, 2009; Muchnik et al., 1991; Röder et al., 2003; Weaver and Stevens, 2007}) \). Moreover, when speech sounds’ perceptual salience are equated on an individual participant level, blind and sighted individuals show equivalent verbal short-term memory spans \( (\text{Rokem and Ahissar, 2009}) \). We did not calibrate our stimuli’s salience to individual thresholds and thus the extent to which perceptual processing efficiencies contributed to the group differences observed here remains unclear.

We further find that blind participants’ short-term memory advantage did not transfer across encoding modalities. In particular, blind participants showed a clear benefit when recalling items encoded auditorily such that span did not differ between forward and backward recall, unlike on the braille digit span. To the extent that span capacity reflects cognitive loads imposed by encoding in the nonpreferred modality \( (\text{De Jong, 2010; Frick, 1984}) \), our findings indicate a preference for auditory encoding over braille. The blind’s auditory backward digit span performance is also notably different from sighted participants, who recalled fewer items in reverse on both auditory and visual span tasks. This finding is consistent with previous reports of improved auditory encoding efficiency in blindness \( (\text{Hötting and Röder, 2009; Muchnik et al., 1991; Rokem and Ahissar, 2009}) \) and indicates that blind participants have sufficiently enhanced span capacity (or compensatory strategies) such that reversing heard items during recall does not tax the cognitive system’s limit. Importantly, this advantage seems to be restricted to the auditory domain.

One inference from modality specificity in the backward recall is that, even for the experienced braille readers in this sample, encoding text processed through hearing is less cognitively demanding than reading in braille. Reasons for the difference in cognitive demand are not entirely clear. Evidence suggests that decoding braille places demands on visuospatial processes, in addition to the verbal demands of maintaining the items in verbal short-term memory. In a previous study, recall on a braille letter span decreased among congenitally blind individuals when completed in conjunction with a spatial interfering task as compared to a verbal interfering task \( (\text{Cohen et al., 2010}) \). Given that congenitally blind individuals’ spatial memory processes are disadvantaged relative to sighted individuals \( (\text{Cornoldi et al., 1991}) \), encoding verbal information in braille may more heavily tax cognitive systems and render braille readers more susceptible to load effects. The differences may also reflect the dominance of accessibility tools such as spoken and text-to-speech technology in daily practice or inherent differences in demands of representing verbal information when encoding text through braille versus speech.

Reading braille is known to require more time than reading print, with even the most experienced braille readers having slower reading rates as compared to print reading \( (\text{Wetzel and Knowlton, 2000}) \). In our study, blind participants were exposed to braille digits for longer durations in order to successfully encode each item. We do not believe, however, that the longer trial durations on the braille digit span tasks would explain the blind’s verbal short-term memory advantage over sighted participants. In a control experiment (completed by sighted participants only), the longer exposure duration did not facilitate recall and instead appeared to promote item decay, potentially due to the longer time between items \( (\text{Ricker et al., 2014}) \). Therefore, we do not attribute our results to increased rehearsal time.

In any memory study, considering age and SES as possible confounds is important. Cognitive sciences is increasingly recognizing the need to include samples and researchers who more accurately represent diverse populations in psychological findings \( (\text{Hötting and Röder, 2009; Medin, 2017; Roberts et al., 2020; Syed, 2017}) \). Our study samples drew from a highly diverse racial/ethnic population (cf. Tables 1 and 2). Blind participants outperformed our full sample of sighted participants, despite the fact that the blind participants included here represent a more socioeconomically diverse and disadvantaged population as compared to the sighted group. We take this as evidence that despite possibly facing double disadvantages due to blindness and SES, blind individuals’ short-term memory capacity is robust to the SES factors that may otherwise adversely impact cognitive functions. To probe this further, an additional analysis of sighted and blind participants matched for age, household income, and maternal education returned similar results as the unmatched sample, with a notably larger effect size despite the
overall smaller sample size. We encourage future studies to include broader SES factors such as household and material income, in addition to age and education. These could contribute to unmask structural factors that otherwise obscure any cognitive advantages.

3.2. N-back

N-back tasks rely more extensively on executive functions as compared to the digit span (Kane et al., 2007). Our study adds to the growing evidence that improved verbal short-term memory may not imply enhanced executive function more generally. Previous work utilizing the n-back in blind and sighted participants finds no impact of visual status on accuracy, although some studies report faster reaction times in the blind populations (Gudi-Mindermann et al., 2018; Park et al., 2011; Pigeon and Marin-Lamellet, 2015, 2017). When comparing n-back accuracy across preferred modalities (visual for the sighted sample, braille for a congenitally blind sample), no between-group differences were found, and blind and sighted populations improved on n-back tasks at equivalent training rates (Bliss et al., 2004; Park et al., 2011).

Like studies before ours, we were careful to match on participants’ age and education (Bliss et al., 2004; Park et al., 2011; Pigeon and Marin-Lamellet, 2017), both of which impact working memory measures. Therefore, we do not attribute our findings to those factors. Instead, our findings suggest that even with congenital or early blindness promoting efficient verbal processing, this efficiency is insufficient to overcome the cognitive demands of manipulating and updating information in verbal working memory.

3.3. Conclusions and future directions

Overall, our data provide evidence that participants who are blind outperform sighted participants on verbal short-term memory digit span tasks. This superiority was most pronounced when encoding items auditorily rather than through braille, evidence for heard speech being less cognitively taxing as compared to reading braille.

Much remains to be understood of memory abilities, namely how visual deprivation contributes to developing these benefits. More research is needed to understand how information modality and encoding may interact, given the advantage we observed for auditory over braille encoding. Based on the importance of SES on working memory development, we recommend future research addresses how susceptible these functions are to stressors, when the benefits emerge developmentally, and if these benefits may be associated with resilience. Importantly, we conclude that blindness contributes to unique cognitive strengths, such as verbal short term memory benefits in blind as
compared to sighted individuals.

4. Experimental procedure

4.1. Participants

Seventy-seven participants volunteered for this study (sighted: N = 58, aged 17–49; mean age = 25.69 ± 8.16; blind: N = 19, aged 22–48; mean age = 28.74 ± 6.98). To be eligible for the study, blind participants could have no more than light perception in the better eye, and their preferred reading medium was braille. Sighted participants had self-reported normal, or corrected to normal vision. All participants were fluent English speakers. Participants were ineligible if they had additional neurological or developmental disabilities, as well as if they had a recent history of illicit drug use. Participants were recruited using snowball sampling and from throughout the university community. Two of the 19 blind participants did not complete the n-back task but were included in the digit span analyses. Additional details on population demographics are shown in Tables 1 and 2.

Both age and SES differed between our two groups’ full samples (cf. Table 1). Therefore, we selected a subset of blind (n = 17) and sighted (n = 17) participants from the larger group, matched on factors of age, maternal education, and family income, for secondary analyses. SES was held equivalent across both groups using the program ‘Match’ (Van Casteren and Davis, 2007).

An additional group of sighted participants (N = 25, aged 18–45; mean age = 21.92 ± 5.18) participated in a control experiment using the visual digit span task (described in further detail below).

4.2. Procedures

The University of California Irvine Human Subjects Institutional Review Board approved all study procedures, and all participants consented prior to participating. Study tasks were controlled using Mac computers running MATLAB (Mathworks, Inc.) with the PsychToolbox (Brainard, 1997). Participants listened to items using the internal computer speakers. Digits for the braille digit span were displayed on Freedom Scientific’s Focus 40 Braille Display. With the exception of the demographic questionnaire, participants inputted responses using an external numeric keypad.

Participants completed two tasks under blindfold: an auditory digit span and an auditory n-back task. Sighted participants additionally completed a visual digit span task, while blind participants completed a braille digit span task (also under blindfold). Participants completed digit span and n-back tasks in counterbalanced order.

4.2.1. Digit span. Participants were presented unique lists of single digits (1–9) in pre-determined orders based on the Wechsler Memory
Participants recalled the digits either in forward or reverse order, with the two tasks completed in separate blocks. To familiarize themselves with the task, participants completed two practice trials per block, followed by the experimental trials. The lists ranged in length from two to twelve items, with two trials completed per list or reverse order, with the two tasks completed in separate blocks. To minimize confusion, maximize clarity, and for standardized letter duration when heard: C, D, G, K, P, Q, T, and V (Jaeggi et al., 2010). Items were recorded using a female voice and were played back for 500 msec with a 1 sec ISI.

An additional group of 10 trials at each n-back level. Participants were required to achieve 70% accuracy (1-back) or 60% (2-back) to proceed to the main task. No minimum accuracy threshold was required for the 3- and 4-back practice trials.

On the main task, each n-back level consisted of three lists with 20 + n trials per list. Each list included six target trials in which the letter matched the n-back item. Two-, three-, and four-back lists included six lures (targets that matched the n-1 or n+1 items). The remaining trials across all n-back lists consisted of filler items. Accuracy and reaction times were recorded. Accuracy was used to compute PR scores, i.e., the difference between proportion hits (correctly identified targets) and proportion false alarms (fillers and lures incorrectly identified as targets). Average PR scores, averaged n-1 and n+1 lure accuracy, and average median correct reaction times (RTs) were used as dependent variables.

### 4.2.3. Digit span timing control experiment

An additional group of sighted participants completed two versions of the visual digit span task: an identical version as in the main experiment in which digits were presented for a 500 msec duration with a 1 sec ISI, and an extended version with a 2.5 sec ISI.

Working memory load increased as a function of n-back level, which ranged from one to four in increasing difficulty across subsequent blocks. The following consonants were selected for the n-back task to minimize confusion, maximize clarity, and for standardized letter duration when heard: C, D, G, K, P, Q, T, and V (Jaeggi et al., 2010). Items were recorded using a female voice and were played back for 500 msec with a 2.5 sec ISI.

### Table 3

Summary of participants, tasks, and results for the full and matched samples.

| Unmatched (Full) Sample | N | F | p | \( \eta^2 \) |
|-------------------------|---|---|---|---------|
| **Task** | **Modality** | **Blind** | **Sighted** | **F** | **p** | **\( \eta^2 \)** |
| Digit Span | **Auditory** | main effect of group | 19 | 58 | 39.82 | 0.000 | 0.35 |
| | | main effect of recall order | | | 3.02 | 0.09 | 0.04 |
| | | recall order \( \times \) group | | | 0.42 | 0.52 | 0.01 |
| | **Visual (exp)** | main effect of modality | – | 58 | 30.57 | 0.000 | 0.35 |
| | | main effect of recall order | | | 18.46 | 0.000 | 0.25 |
| | | recall order \( \times \) modality | | | 1.49 | 0.23 | 0.03 |
| | **Braille** | main effect of modality | 19 | – | 20.15 | 0.000 | 0.53 |
| | | main effect of recall order | | | 19.89 | 0.000 | 0.53 |
| | | recall order \( \times \) modality | | | 8.46 | 0.01 | 0.32 |
| | **Visual (timing control)** | main effect of digit duration | – | 25 | 26.88 | 0.000 | 0.53 |

| Matched (sub) Sample | N | F | p | \( \eta^2 \) |
|----------------------|---|---|---|---------|
| **Task** | **Modality** | **Blind** | **Sighted** | **F** | **p** | **\( \eta^2 \)** |
| Digit Span | **Auditory** | main effect of group | 17 | 17 | 30.43 | 0.000 | 0.49 |
| | | main effect of recall order | | | 2.297 | 0.14 | 0.07 |
| | | recall order \( \times \) group | | | 0.404 | 0.53 | 0.01 |
| N-Back | **Auditory** | main effect of group | 17 | 17 | 2.10 | 0.16 | 0.06 |
| | | n-back level \( \times \) group | | | 0.70 | 0.56 | 0.02 |
| | | main effect of n-back | | | 2.74 | 0.11 | 0.08 |
| | | n-back level \( \times \) group | | | 1.22 | 0.31 | 0.04 |

4.2.2. **Auditory n-back.** Participants heard letters and identified whether or not the current letter matched the letter heard n positions back on the list by key press (‘4’ for targets, and ‘6’ for non-targets).
Supplementary data to this article can be found online at https://doi.org/10.1016/j.brainres.2020.11.012.
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