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Short-term and Working Memory in Blind and Sighted Individuals

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Short-Term and Working Memory in Blind and Sighted Individuals

DISSERTATION

submitted in partial satisfaction of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

in Cognitive Sciences with a Concentration in Cognitive Neuroscience

by

Karen Arcos

Dissertation Committee:
Professor Emily D. Grossman, Chair
Associate Professor Susanne M. Jaeggi
Associate Professor Marina Bedny
Associate Professor Ana Rosas
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2020

DEDICATION

This dissertation is dedicated to my family, especially to my parents. To my mom for teaching me to live by the following lines:

“Estudia, y no serás, cuando crecido,

Ni el juguete vulgar de las pasiones,

Ni el esclavo servil de los tiranos.”

(“Study, and you will not be, when grown,

Neither the vulgar toy of passions,

Nor the servile slave of tyrants.” Elias Calixto Pompa)

To my father for praising my writing growing up, for prioritizing education, and for telling me “the way it is.” Dad, I continue remembering you and using your passion for justice and equity to motivate me forward.

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ACKNOWLEDGEMENTS

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I would especially like to thank my advisor, Dr. Emily Grossman, for welcoming me in to her lab and supporting me in conducting research on a topic outside her immediate expertise. I appreciate her patience with teaching me computer programming, her openness to learn about accessibility, as well as all her oral and written feedback.

Special thanks as well to my co-advisor, Dr. Susanne Jaeggi, for improving my understanding and appreciation of statistics, for creating a strong sense of community in her lab, for being inclusive, and for keeping me grounded and focused through her oral and written feedback.

I would also like to acknowledge my additional committee members. Dr. Marina Bedny, for allowing me to analyze and include her dataset in my dissertation, as well as for making me think more deeply about scientific writing. Dr. Ana Rosas for normalizing the value of family, for empathizing with me as a Latina, and for her optimism. Thank you to Dr. Sara Mednick for her support as well.

I am very grateful to the Disability services Center and to the many research assistants I interacted with to accommodate my needs. Thank you as well to the Braille Institute of America in Los Angeles, The National Federation of the Blind, Blind Children's Center, and Wayfinder Family Services for assistance with recruiting study participants. I appreciate the Chicano/Latino studies department, Graduate Division, Division of Career pathways, and the Graduate & Postdoctoral Scholar Resource Center for their career-related support as well.

Funding was provided by the National Science Foundation Graduate Research Fellowship Program and UC Irvine's Faculty Mentor Program.

VITA

Karen Arcos

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University of California, Irvine December 2020
PhD in Psychology (Cognitive Neuroscience) and Chicano/Latino Studies Emphasis
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RESEARCH EXPERIENCE

Visual Perception and Neuroimaging Lab September 2015-Present
University of California Irvine, Irvine, CA
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Laboratorio Colcan S.A.S. Bogotá Colombia December 2019
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Neuroplasticity and Development Lab June 2018-August 2018
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- Analyzed and collected data for a working memory experiment in MATLAB to assess verbal and nonverbal working memory among blind relative to sighted individuals

PUBLICATIONS

WORKS IN PROGRESS
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Arcos, K., Harhen, N., Loiotile, R.E., & Bedny, M. **Superior Verbal over Nonverbal Memory in Congenital Blindness.**

WORKS FOR POPULAR AUDIENCES
Arcos, K. (2019). A Breeze Through Brain Land. *STEMTaught*.

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University of California, Irvine ($43,751.50), Irvine, CA
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Psychonomic Society Annual Meeting November 2018
New Orleans, LA
- "**Variations in Memory Ability in Sighted and Unsighted Individuals**"

Gordon Research Conference on Neurobiology of Cognition July 2018
Newry, ME
- "**Variations in Memory Ability in Sighted and Unsighted Individuals**"

Gordon Research Seminar on Neurobiology of Cognition July 2018
Newry, ME
- "**Variations in Memory Ability in Sighted and Unsighted Individuals**"

Rice University Scientia Institute Discussant March 2018
Houston, TX
- **“Interdisciplinary Research Perspectives on Braille Reading and Writing”**

American Evaluation Association November 2015
Chicago, IL
- "**What Teachers Know: Relationships of teacher competencies around content knowledge, metacognition, and student prior knowledge to student performance in science**"

SYMPOSIA

Associated Graduate Students Symposium Presenter April 2018 and April 2019
University of California Irvine, Irvine, CA
- “**Blanketing Out Before Breakfast**” and “**Memory Madness**

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Grad Slam Finals March 2019 and February 2020

University of California Irvine, Irvine, CA
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PROFESSIONAL SERVICE

Sample documents for Division of Career Pathways 2020
University of California Irvine, Irvine, CA
- Provided CV and resumé as samples for website galleries

Guest reviewer for INTELL journal 2019
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- Provided feedback on article’s scientific content and experimental design

PROFESSIONAL DEVELOPMENT

Activate to Captivate January 2020-March 2020
University of California Irvine, Irvine, CA
- Implemented visual, verbal, and nonverbal strategies to communicate research to scientific and nonscientific audiences

Loh Down on Science Fellow April 2018-September 2020
University of California Irvine, Irvine, CA
- Wrote over 15 scripts on current scientific research for national radio broadcast for non-scientific audiences

Mentoring Excellence Program July 2017-August 2017
University of California Irvine, Irvine, CA
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- Addressed relationship ethics, diversity, and conflict resolution

LEADERSHIP EXPERIENCE

Diverse Educational Community and Doctoral experience (DECADE)
University of California, Irvine, Irvine, CA
Campus Council Representative for Cognitive Sciences October 2019-December 2020
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Chicano Latino Graduate Student Collective Recorder and Treasurer September 2018-June 2019
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SKILLS
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ABSTRACT OF THE DISSERTATION

Short-term and Working Memory in Blind and Sighted Individuals
By Karen Arcos
Doctor of Philosophy in Cognitive Sciences with a Concentration in Cognitive Neuroscience
University of California, Irvine, 2020
Professor Emily D. Grossman, Chair

This thesis examines the impact of visual deprivation on memory abilities. Although some studies report those who are blind appear to exhibit larger short-term memory (STM) capacity relative to the sighted, the extent to which this generalizes to nonverbal information and more complex memory tasks is unclear. The first chapter presents results of a systematic review evaluating visual deprivation's impact on STM and on working memory (WM). Age of blindness onset, stimulus type, and demographics are possible factors explaining discrepancies across studies.

Subsequent chapters detail the results of two empirical studies exploring the roles of verbal and nonverbal stimuli along with sensory modality in STM and WM among individuals who are sighted and visually impaired. In a test of verbal and nonverbal memory, sighted and congenitally blind adults completed a battery of auditory short-term, working, and recognition memory tasks using difficulty-matched verbal and nonverbal information. These results find that while blind individuals exhibit a verbal memory advantage over sighted individuals, their advantage is eliminated for nonverbal memory.

A second set of experiments investigates how socioeconomic status (SES) and information encoded through different senses may impact STM and WM in adults who are legally blind and

sighted. Overall, blind participants outperformed sighted ones on both the STM and simpler WM tasks. Critically, blind participants also outperformed sighted participants on a more complex WM task, but this group difference only appeared when SES factors were equated across the groups. Moreover, whereas sighted participants had improved STM for items encoded visually as compared to for items heard orally, blind participants performed equally well between braille encoded and heard information. Thus, STM performance in individuals who are blind appears to extend to robust encoding through multiple sensory modalities.

In conclusion, the data from these three studies suggests considering whether stimuli are verbal or nonverbal and encoding modality are important for memory. Overall, the findings presented here are consistent with the hypothesis that in cases when blind individuals exhibit a memory advantage over the sighted, it is linked to experience-dependent plasticity. These findings have potential to aid in designing more effective educational and rehabilitative interventions capitalizing on the increased capacity for verbal memory in blindness.

INTRODUCTION

Our experience is key to shaping the ways in which our cognitive abilities develop. One critical cognitive skill is the ability to actively manipulate information in our minds, WM, which humans rely on in everyday life. From navigating unfamiliar environments to recalling information after being distracted, WM is critical for storing information, processing it, and for effective problem-solving. It also supports cognitive abilities such as learning, reasoning, and comprehension (Baddeley, 2003).

WM is especially important for individuals who experience sensory deprivation, such as those who are blind. Individuals who are blind must rely on WM to manipulate and recall information that sighted individuals can acquire visually, i.e., memorizing verbal descriptions of routes to a destination rather than using a spatial map in conjunction with visual cues. Researchers have hypothesized those who are blind may benefit from daily use of WM abilities, potentially resulting in WM benefits. This thesis explored how visual deprivation impacts STM and WM abilities in blind as compared to sighted adults. We specifically tested whether those who are blind demonstrate better WM performance as compared to sighted individuals under certain conditions. The first chapter systematically reviews literature testing STM and WM performance in blind and sighted humans. Some evidence exists for superior memory abilities in blind as compared to sighted individuals. Participants in studies of children (Hull & Mason, 1995; Smits & Mommers, 1976; Withagen, Kappers, Vervloed, Knoors, & Verhoeven, 2013) and adults (Bottini, Mattioni, & Collignon, 2016; Dormal, Crollen, Baumans, Lepore, & Collignon, 2016) have found blind individuals appear to have a verbal WM advantage as compared to the sighted. In these studies, blind participants recalled digits, letters, and words in forward or reverse order and amidst interfering tasks better than sighted individuals. While explicit rehearsal may have taken place in the majority of the above studies, evidence suggests that the advantage in blind individuals' may persist when interference precludes rehearsal (Dormal et al., 2016; Röder, Rösler, & Neville, 2001; Withagen et al., 2013).

The above studies may have found that blind individuals outperformed the sighted due to using similar stimuli—verbal items. However, other studies with varied study designs find no differences in WM performance between blind and sighted individuals. Again, null results are found in both children (Bathelt, de Haan, Salt, & Dale, 2018; Ekstrom, 2018; Swanson & Luxenberg, 2009 on a backward digit span) and adults (Castronovo & Delvenne, 2013; Park et al., 2011; Pigeon & Marin-Lamellet, 2015). Though they find nonsignificant group differences, these studies vary with respect to stimulus types, participant demographics, and procedures used. While verbal material was used in all of the above studies, no differences have been found when using nonverbal stimuli, suggesting factors other than verbal and nonverbal stimuli may explain the performance differences (Gudi-Mindermann et al., 2018; Park et al., 2011). Therefore, what may contribute to these discrepant findings remains uncertain.

An important aspect that researchers have yet to systematically assess in existing literature is demographic factors that may contribute to memory performance differences between blind and sighted individuals. Characteristics such as age, academic achievement, and income are associated with WM development (Hackman et al., 2014; Hartshorne & Germine, 2015; Swanson & Alloway, 2012). WM ability improves with age From childhood through early adulthood, then declines (Hartshorne & Germine, 2015). Because individuals of lower SES are exposed to less complex language early in development relative to those of high SES (Ursache & Noble, 2016), the extent to which their WM may develop during this critical window is affected, and they may be disadvantaged with respect to academics for reasons including lack of access to relevant resources (Bradley & Corwyn, 2002). Some studies control for factors associated with SES, whereas others fail to in spite of their relevance (Castronovo & Delvenne, 2013; Pigeon & Marin-Lamellet, 2017). Drawing conclusions is challenging due to the unsystematic ways participants are matched. By clarifying the factors that contribute to the between-group differences, we can better understand the magnitude of the difference and why blind individuals may have higher memory abilities under certain conditions and not others.

Based on the inconsistent evidence on memory performance in individuals who are blind and sighted, this thesis seeks to bring some cohesiveness to the literature while also assessing three areas that may contribute to possible memory performance differences. First, a review of varied WM studies systematically compares memory performance in blind and sighted individuals. It also evaluates the extent to which modality and verbal and nonverbal stimuli may contribute to the memory performance differences in blind as compared to sighted participants. We then present three experiments that explore the influence of verbal and nonverbal stimuli on WM in blind and sighted individuals. An additional experiment assesses the impacts of modality and SES on STM and WM performance. By studying how aspects such as stimulus type influence memory performance, this thesis hopes to clarify if differences emerge depending on whether or not linguistic material is being memorized since the majority of studies employ auditory verbal tasks (Occelli, Lacey, Stephens, Merabet, & Sathian, 2017; Pasqualotto, Lam, & Proulx, 2013; Pigeon & Marin-Lamellet, 2017; Rindermann, Ackermann, & Te Nijenhuis, 2020; Rokem & Ahissar, 2009; Tillman & Bashaw, 1968).

Because WM ability also varies as a function of SES (Ursache & Noble, 2016), this thesis also considers the role of SES factors on memory performance. Matching for SES factors is critical in executive function studies that develop in the context of environmental factors, with potential to uncover cognitive benefits that may emerge through experience-based neuroplasticity for individuals whose abilities are typically considered through a deficit model (Monedero, Cuesta, & Angulo, 2014). Carefully examining these factors may partly clarify why memory differences emerge and clearly support the importance of including factors other than blindness in research to draw more accurate conclusions on memory differences.

The ability to recall information effectively partly depends on the cognitive load during encoding, which varies with preferred sensory modalities (Frick, 1984). The majority of prior work fails to consider encoding modality when comparing performance differences across blind and sighted populations. We will test groups' STM and WM cross-modally to understand if memory is differentially impacted per group depending on the encoding modality in use.

Chapter 1

Working Memory in Blindness Review

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Abstract

WM is a key cognitive function for completing everyday tasks such as maintaining the thread of ideas in a conversation. Individuals who are blind especially rely on WM to complete tasks the sighted may complete visually, i.e., locating items. Existing literature assessing WM differences between blind and sighted participants is mixed regarding whether or not visual deprivation is linked to superior memory abilities relative to the sighted. Early blinded individuals recall significantly more items than sighted individuals following interfering tasks, whereas those who lose their vision later in life do not. However, the type of stimuli being encoded may also influence differences in that blind individuals have demonstrated greater WM performance on verbal span tasks and on those using nonverbal stimuli. Therefore, this review aims to clarify the roles of age of blindness onset and stimulus type on these differences using effect sizes while also exploring the impacts of demographic characteristics, SES, and modality on participants' memory abilities. Between-group differences are shown most in studies of early blind participants when evaluated using verbal stimuli. We recommend exploring SES and modality in future work because of their links to WM scores in sighted populations.

Introduction

Humans use STM and WM) on a daily basis. From maintaining a conversation to navigating familiar and unfamiliar environments amidst distraction, STM and WM are involved. Moreover, WM is predictive of academic achievement (Rohde & Thompson, 2007). Therefore, our WM is critical for us to perform tasks optimally.

Individuals who are blind rely extensively on memory to compensate for their lack of vision when completing tasks that sighted individuals may execute visually (such as identifying items differentiated by printed labels). Blind individuals' frequent memory use, therefore, may result in enhanced memory abilities honed through practice. Past studies have documented an STM advantage in blind over sighted participants during both childhood and adulthood (Rokem & Ahissar, 2009; Tillman & Bashaw, 1968; Withagen et al., 2013), with between-group differences emerging at age six and remaining constant over time (Hull & Mason, 1995).

Less consensus exists on whether blind individuals exhibit a WM advantage as compared to the sighted. Some studies show an advantage in blind and sighted children and adults (Bliss, Kujala, & Hämäläinen, 2004; Smits & Mommers, 1976; Tillman & Bashaw, 1968; Withagen et al., 2013), while other studies find no differences between the groups (Park et al., 2011; Pigeon & Marin-Lamellet, 2015; Rokem & Ahissar, 2009). The reasons for these discrepancies are unclear but could include samples unmatched on factors impacting plasticity of cognitive and neural mechanisms in blindness (e.g. age of visual impairment onset), the cognitive load associated with the studies' encoding methods, unaccounted demographic differences between the two populations disadvantaging one over the other, or publication bias favoring group differences that may not actually exist.

This review aims to unify and consolidate existing findings regarding WM among individuals who are blind and sighted, with the goals of evaluating the extent to which such differences exist when considering the literature holistically and identifying what factors may contribute to any discrepancies between studies. We systematically document effect sizes from peer-reviewed empirical journal articles testing for group differences on WM-related tasks. We collate these effect sizes across studies to identify patterns based on certain factors that may influence WM differences between blind and sighted individuals, including age of blindness onset, stimulus type, modality, WM load, and demographics. We aim to objectively measure WM performance across groups and directly compare the magnitude of such differences across studies because articles vary with respect to procedures, sample characteristics, tasks, etc. Therefore, we focus on potential mechanisms in existing literature that seem to impact WM performance among blind and sighted individuals.

Characteristics influencing Blind individuals' WM performance

Influence of blindness onset

Early visual impairment onset may promote using memory strategies early in life that impact blind participants' memory abilities. WM develops in childhood, continuing through early adulthood, then declines with older age (Hartshorne & Germine, 2015). Thus, we would expect any WM adaptations associated with blindness to greatly impact if visual impairment onset occurs before adulthood.

Evidence exists for neural plasticity in sensory cortex for individuals with early onset blindness. At least one study finds the neural activity in congenitally blind individuals' occipital cortex (but not sighted individuals') is correlated with their performance on long-term memory tasks, implying a functional role of visual cortex in memory (Amedi, Raz, Pianka, Malach, & Zohary, 2003). Moreover, left occipital cortex activates during linguistic tasks when responding to heard sentences in congenitally blind, but not late blind, individuals (Bedny, Pascual-Leone, Dravida, & Saxe, 2012). This activation difference implies vision may need to be lost during an early sensitive period in order for occipital cortex to respond to language.

Early and late blind individuals use different spatial memory strategies, with early blind individuals relying strongly on traveling in serial routes (Raz, Striem, Pundak, Orlov, & Zohary, 2007). Early blind individuals estimate distances better using route based descriptions versus survey descriptions, which are better for late blind and sighted individuals (Noordzij, Zuidhoek, & Postma, 2006). Indeed, adults who become blind early in life do not experience spatially-based ordinal position effects when recalling word lists, something observed in late blind and sighted individuals(Bottini et al., 2016). This contrast indicates that individuals who lose their sight early in life may not use spatial cues to organize information to the extent that late blind and sighted individuals do.

One complicating factor is that studies vary with respect to the criterion used to consider participants as early or late blind, leading to inconsistency with respect to how studies categorize early and late blind participants. Whereas some studies' late blind participants were diagnosed as early as age three or later (Bottini et al., 2016), other studies late blind participants were diagnosed beginning at age 16 (Dormal et al., 2016). Studies whose participants became blind after birth would benefit from defining early vs. late onset more consistently to more systematically interpret how results compare across studies and possibly explain what contributes to this difference.

Impact of Verbalizing Stimuli

In addition to blindness onset's influence, whether or not stimuli are verbalizable may also impact performance. According to the Baddeley and Hitch WM model, the visuospatial sketchpad holds and manipulates spatial information. The phonological loop, another component of the model, uses acoustic characteristics to manipulate linguistic information (Baddeley, 2003). Verbal and spatial information are believed to rely on distinct mechanisms in WM.

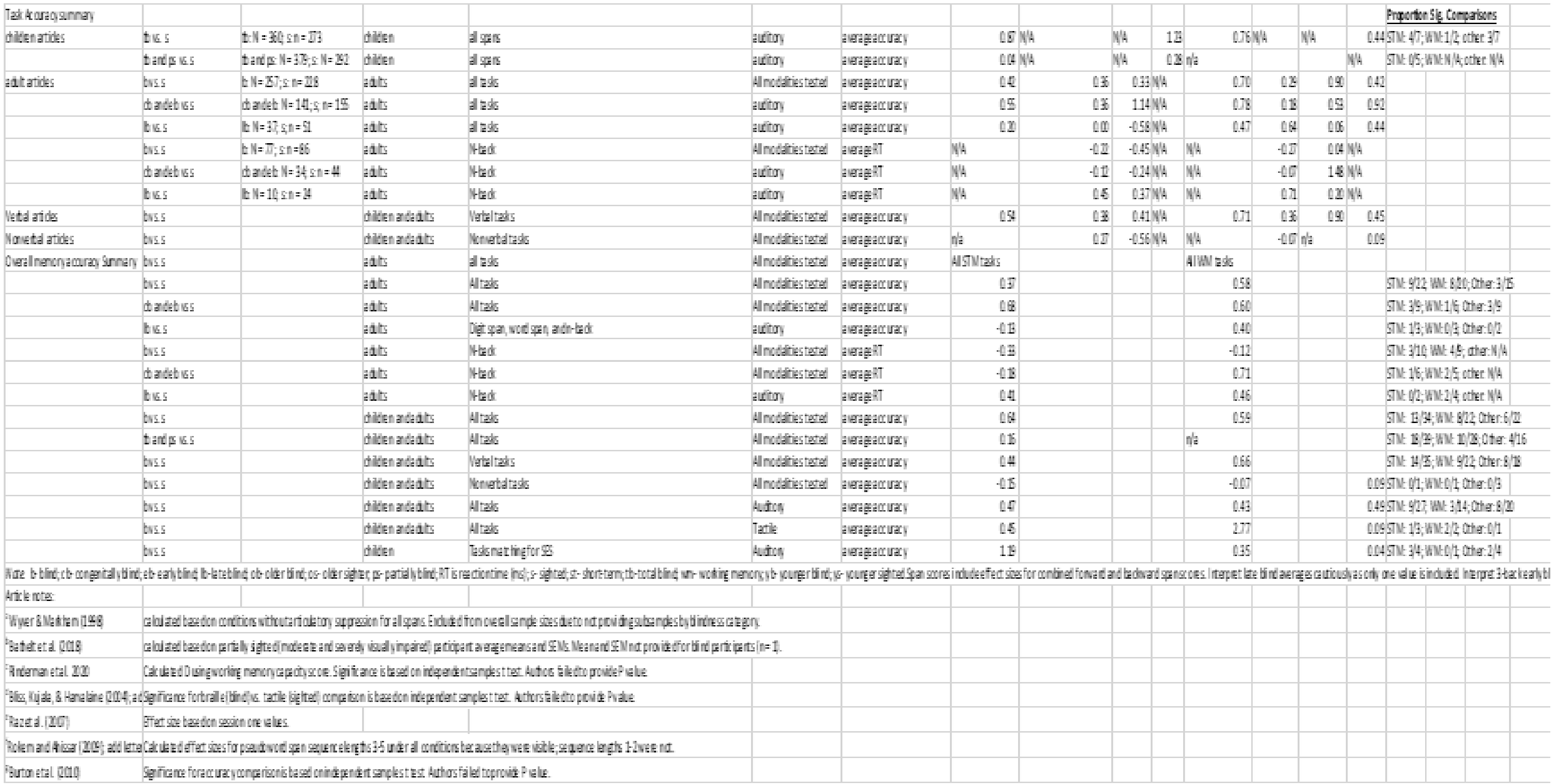
As a result of lacking visual cues to interact in their surroundings, blind individuals may rely on auditory cues, which are primarily verbalizable. Those who are blind attribute verbal labels to both linguistic information (i.e. verbal descriptions) and to nonverbal but verbalizable information (i.e. opening and closing door sounds) when orienting to their environments (Williams, Galbraith, Kane, & Hurst, 2014), thus possibly giving them more practice with interpreting verbalizable information relative to sighted individuals. Blind individuals' greater practice using verbalizable information may give them a specific advantage with recalling verbal over nonlinguistic items.

The vast majority of studies that document superior memory in blindness use verbal memory tasks, and the effects generally become smaller and sometimes nonsignificant when the recalled items are difficult to verbalize. Blind individuals perform better than sighted ones when recalling words and numbers (Occelli et al., 2017; Raz et al., 2007; Rokem & Ahissar, 2009), as well as on WM tasks involving manipulating digits (Occelli et al., 2017). This memory benefit persists when completing nonverbal interfering tasks designed to prevent verbal rehearsal (Dormal et al., 2016). Indeed, blind individuals continue to outperform the sighted on verbal recall tasks even when the interference component includes verbal content (cf`. table 1.1; Bottini et al., 2016)

Tab+A1:K55le 1.1

Effect Size Cohen's d (blind and sighted comparison)

Authors	Comparison(population)	Sample sizes	Age	Task	Modality	Dependent variable	Short-Term Memory				Working Memory			
							Forward span	0-back	1-back	Span	Backward span	2-back	3-back	Other
Tillman & Bashaw (1968)	b vs. s	b: n = 167; s: n unknown	children	digit span	auditory	accuracy				0.65				
Smits and Mommers (1976)	tb and ps vs. s	tb: n = 92; ps: n = 97; s: n = 96	children	digit span	auditory	accuracy				0.44				
	tb vs. s	tb: n = 92; s: n = 96	children	digit span	auditory	accuracy				0.60				
	ps vs. s	ps: n = 97; s: n = 96	children	digit span	auditory	accuracy				0.31				
[a]Wyver & Markham (1998)	b and ps vs. s	b and ps: n = 19 and s: n = 19	children	digit span	auditory	accuracy	-0.08							
	b and ps vs. s	b and ps: n = 19 and s: n = 20	children	word span (one syllable)	auditory	accuracy	-0.19							
	b and ps vs. s	b and ps: n = 19 and s: n = 21	children	word span (three syllables)	auditory	accuracy	0.25							
	b and ps vs. s	b and ps: n = 19 and s: n = 22	children	word span (phonologically similar)	auditory	accuracy	-0.10							
	b and ps vs. s	b and ps: n = 19 and s: n = 23	children	non-word span (one syllable)	auditory	accuracy	0.34							
Swanson & Luxenberg (2009)	b vs. s	b: n = 17; s: n = 19	children	digit span expt 1	auditory	accuracy				1.54				
	b vs. s	b: n = 17; s: n = 25	children	digit span expt 2	auditory	accuracy	1.21				0.35			
	b vs. s	b: n = 17; s: n = 19	children	STM Word span expt 1	auditory	accuracy	0.65							
	b vs. s	b: n = 17; s: n = 25	children	STM Rhyming word span expt 2	auditory	accuracy	2.35							
	b vs. s	b: n = 17; s: n = 19	children	STM Sentence span expt 1	auditory	accuracy	0.55							
	b vs. s	b: n = 17; s: n = 25	children	WM Digits (recalling address expt 1)	auditory	accuracy								0.74
	b vs. s	b: n = 17; s: n = 26	children	WM categorizing words (expt 1)	auditory	accuracy								0.33
	b vs. s	b: n = 17; s: n = 27	children	WM sentences (story retelling expt 1)	auditory	accuracy								-0.58
	b vs. s	b: n = 17; s: n = 19	children	WM Sentence span expt 2	auditory	accuracy								-0.34
Withagen et al. (2013)	cb vs. s	cb: n = 14; s: n = 13	children	digit span	auditory	accuracy	0.06				1.17			
	cb vs. s	cb: n = 14; s: n = 14	children	STM: 15 word recall	auditory	accuracy				2.14				
	cb vs. s	cb: n = 14; s: n = 15	children	STM: learning names of nonverbalizable objects	auditory	accuracy								2.12
	cb vs. s	cb: n = 14; s: n = 16	children	WM: listening span	auditory	accuracy								1.18
[b]Bathelt et al. (2018)	ps vs. s	ps: n = 17; s: n = 18	children	digit span	auditory	accuracy				0.11				
	ps vs. s	ps: n = 17; s: n = 19	children	Letter-Number Sequence	auditory	accuracy								-0.34
Ekstrom (2018)	cb vs. s	cb: n = 6; s: n = 6	adolescents	digit span	auditory	accuracy	0.68							
	cb vs. s	cb: n = 6; s: n = 7	adolescents	non-word repetition	auditory	accuracy	0.58							
[c]Rinderman et al. 2020	b vs. s	b: n = 64; s: n = 96	Children and Adolescents	Forward digit span, backward digit span, and letter-number sequencin	auditory	accuracy								1.02
[d]Bliss, Kujala, & Hamalaine (2004)	b vs. s	b: n = 21; s: n = 16	adults	letter N-back	braille (b) vs. tactile (s)	incorrect accuracy		1.05	1.41			1.59	2.12	
	b vs. s	b: n = 21; s: n = 17	adults	letter N-back	braille (b) vs. visual (s)	incorrect accuracy		0.47	-0.53			-0.53	-0.44	
	b vs. s	b: n = 21; s: n = 18	adults	letter N-back	tactile (b) vs. tactile (s)	incorrect accuracy		0.54	1.35			1.44	4.11	
	b vs. s	b: n = 21; s: n = 19	adults	letter N-back	tactile (b) vs. visual (s)	incorrect accuracy		-0.20	-0.54			-0.76	1.35	
[e]Raz et al. (2007)	cb vs. s	cb: n = 19; s: n = 19	adults	Word span	auditory	accuracy	1.13							
[f]Rokem and Ahissar (2009)	cb vs. s	cb: n = 16; s: n = 16	adults	digit span	auditory	accuracy	1.74				0.55			
	cb vs. s	cb: n = 16; s: n = 17	adults	Pseudoword span (supra-threshold, all sequence lengths)	auditory	accuracy	0.63							
	cb vs. s	cb: n = 16; s: n = 18	adults	Pseudoword span (supra-threshold, sequence length 3)	auditory	accuracy	0.79							
	cb vs. s	cb: n = 16; s: n = 19	adults	Pseudoword span (supra-threshold, sequence length 4)	auditory	accuracy	0.57							
	cb vs. s	cb: n = 16; s: n = 20	adults	Pseudoword span (supra-threshold, sequence length 5)	auditory	accuracy	0.78							
	cb vs. s	cb: n = 16; s: n = 21	adults	Pseudoword span (80% threshold in noise, sequence length 3)	auditory	accuracy	-0.53							
	cb vs. s	cb: n = 16; s: n = 22	adults	Pseudoword span (80% threshold in noise, sequence length 4)	auditory	accuracy	-0.11							
	cb vs. s	cb: n = 16; s: n = 23	adults	Pseudoword span (80% threshold in noise, sequence length 5)	auditory	accuracy	0.34							
	cb vs. s	cb: n = 16; s: n = 24	adults	Pseudoword span (80% threshold in quiet, sequence length 3)	auditory	accuracy	0.39							
	cb vs. s	cb: n = 16; s: n = 25	adults	Pseudoword span (80% threshold in quiet, sequence length 4)	auditory	accuracy	0.48							
	cb vs. s	cb: n = 16; s: n = 26	adults	Pseudoword span (80% threshold in quiet, sequence length 5)	auditory	accuracy	0.45							
[g]Burton et al. 2010	eb vs. s	eb: n = 10; s: n = 10	adults	n-back vibration task	Tactile	accuracy			-0.56					
	eb vs. s	eb: n = 10; s: n = 11	adults	n-back vibration task	Tactile	RT			0.58					
Park et al. (2011)	cb vs. s	cb: n = 10; s: n = 10	adults	word N-back	auditory	accuracy		0.18				0.43		
	cb vs. s	cb: n = 10; s: n = 11	adults	pitch N-back	auditory	accuracy		0.00				0.00		
	cb vs. s	cb: n = 10; s: n = 12	adults	sound location N-back	auditory	accuracy		0.53				-0.19		
	cb vs. s	cb: n = 10; s: n = 13	adults	word N-back	auditory	RT		-0.75				-0.63		
	cb vs. s	cb: n = 10; s: n = 14	adults	pitch N-back	auditory	RT		-0.26				-0.36		
	cb vs. s	cb: n = 10; s: n = 15	adults	sound location N-back	auditory	RT		-0.13				-0.66		
Castronovo and Delvenne (2013)	cb vs. s	cb: n = 11; s: n = 11	adults	digit span	auditory	accuracy	0.55				0.25			
	cb vs. s	cb: n = 11; s: n = 12	adults	word span	auditory	accuracy	0.86							
Kattner and Ellermeier (2014)	b vs. s	b: n = 15; s: n = 15	adults	matching short word to list position with speech	auditory	accuracy								0.25
	b vs. s	b: n = 15; s: n = 16	adults	matching short word to list position with noise	auditory	accuracy								-0.18
	b vs. s	b: n = 15; s: n = 17	adults	matching long word to list position with speech	auditory	accuracy								-0.2
	b vs. s	b: n = 15; s: n = 18	adults	matching long word to list position with noise	auditory	accuracy								0.28
Pigeon & Marin-Lamellet (2015)	eb vs. s	eb: n = 14; s: n = 24	adults	letter N-back and digit span	auditory	accuracy	0.12	0.71	2.83		0.66	0.47	0.53	
	lb vs. s	lb: n = 10; s: n = 24	adults	letter N-back and digit span	auditory	accuracy	0.20	0.00	-0.58		0.47	0.64	0.06	
	eb vs. s	eb: n = 14; s: n = 24	adults	letter N-back	auditory	RT		0.65	-1.05			1.37	1.48	
	lb vs. s	lb: n = 10; s: n = 24	adults	letter N-back	auditory	RT		0.45	0.37			0.71	0.20	
Bottini et al. (2016)	eb vs. s	eb: n = 14; s: n = 15	adults	Word recall with interference	auditory	accuracy								1.1
	lb vs. s	lb: n = 15; s: n = 15	adults	Word recall with interference	auditory	accuracy								0.66
Dormal et al. (2016)	eb vs. s	eb: n = 10; s: n = 12	adults	forward letter span and pitch discrimination interference	auditory	accuracy								1.56
	lb vs. s	lb: n = 12; s: n = 12	adults	forward letter span and pitch discrimination interference	auditory	accuracy								0.21
Occelli et al. (2017)	cb vs. s	c: n = 12; s: n = 13	adults	backward digit span	auditory	accuracy					1.67			
	cb vs. s	cb: n = 12; s: n = 13	adults	Corsi block task	Tactile	accuracy								0.09
Pigeon & Marin-Lamellet (2017)	yb vs. ys	yb: n = 27; ys: n = 24	adults	digit span and letter N-back	auditory	accuracy	0.26	0.00	-0.26		0.80	0.53	0.26	
	ob vs. os	ob: n = 16; os: n = 18	adults	digit span and letter N-back	auditory	accuracy	-0.24	0.71	0.39		0.46	-0.23	0.48	
	yb vs. os	yb: n = 27; os: n = 18	adults	digit span and letter N-back	auditory	accuracy	0.47	0.00	0.38		1.43	1.12	1.05	
	ob vs. ys	ob: n = 16; ys: n = 24	adults	digit span and letter N-back	auditory	accuracy	-0.46	0.71	-0.32		0.00	-0.73	-0.50	
	yb vs. ys	yb: n = 27; ys: n = 24	adults	digit span and letter N-back	auditory	RT		-0.55	-0.64			-0.97	-0.63	
	ob vs. os	ob: n = 16; os: n = 18	adults	digit span and letter N-back	auditory	RT		-0.34	-0.80			-0.41	-0.15	
	yb vs. os	ybd: n = 27; os: n = 18	adults	digit span and letter N-back	auditory	RT		-1.28	-1.93			-1.84	-0.70	
	ob vs. ys	ob: n = 16; ys: n = 24	adults	digit span and letter N-back	auditory	RT		0.28	0.35			0.34	0.02	
Gudi-Mindermann et al. (2018)	cb vs. s	cb: n = 25; s: n = 25	adults	N-back (pre-training)	tactile and auditory	average accuracy (all tasks)						-0.02		



Task Accuracy summary															Proportion Sig. Comparisons
children articles	tb vs. s	tb: N = 360; s: n = 273	children	all spans	auditory	average accuracy	0.67	N/A	N/A	1.23	0.76	N/A	N/A	0.44	STM: 4/7; WM: 1/2; other: 3/7
	tb and ps vs. s	tb and ps: N = 379; s: N = 292	children	all spans	auditory	average accuracy	0.04	N/A	N/A	0.28	n/a			N/A	STM: 0/5; WM: N/A; other: N/A
adult articles	b vs. s	b: N= 257; s: n= 228	adults	all tasks	All modalities tested	average accuracy	0.42	0.36	0.33	N/A	0.70	0.29	0.90	0.42	
	cb and eb vs. s	cb and eb: N= 141; s: n= 155	adults	all tasks	auditory	average accuracy	0.55	0.36	1.14	N/A	0.78	0.18	0.53	0.52	
	lb vs. s	lb: N= 37; s: n = 51	adults	all tasks	auditory	average accuracy	0.20	0.00	-0.58	N/A	0.47	0.64	0.06	0.44	
	b vs. s	b: N= 77; s: n = 86	adults	N-back	All modalities tested	average RT	N/A	-0.22	-0.45	N/A	N/A	-0.27	0.04	N/A	
	cb and eb vs. s	cb and eb: N= 34; s: n = 44	adults	N-back	auditory	average RT	N/A	-0.12	-0.24	N/A	N/A	-0.07	1.48	N/A	
	lb vs. s	lb: N= 10; s: n = 24	adults	N-back	auditory	average RT	N/A	0.45	0.37	N/A	N/A	0.71	0.20	N/A	
Verbal articles	b vs. s		children and adults	Verbal tasks	All modalities tested	average accuracy	0.54	0.38	0.41	N/A	0.71	0.36	0.90	0.45	
Nonverbal articles	b vs. s		children and adults	Nonverbal tasks	All modalities tested	average accuracy	n/a	0.27	-0.56	N/A	N/A	-0.07	n/a	0.09	
Overall memory accuracy Summary	b vs. s		adults	all tasks	All modalities tested	average accuracy	All STM tasks				All WM tasks				
	b vs. s		adults	All tasks	All modalities tested	average accuracy	0.37				0.58				STM: 9/22; WM: 8/20; Other: 3/15
	cb and eb vs. s		adults	All tasks	All modalities tested	average accuracy	0.68				0.60				STM: 3/9; WM: 1/6; Other: 3/9
	lb vs. s		adults	Digit span, word span, and n-back	auditory	average accuracy	-0.13				0.40				STM: 1/3; WM: 0/3; Other: 0/2
	b vs. s		adults	N-back	All modalities tested	average RT	-0.33				-0.12				STM: 3/10; WM: 4/9; other: N/A
	cb and eb vs. s		adults	N-back	All modalities tested	average RT	-0.18				0.71				STM: 1/6; WM: 2/5; other: N/A
	lb vs. s		adults	N-back	auditory	average RT	0.41				0.46				STM: 0/2; WM: 2/4; other: N/A
	b vs. s		children and adults	All tasks	All modalities tested	average accuracy	0.64				0.59				STM: 13/34; WM: 8/22; Other: 6/22
	tb and ps vs. s		children and adults	All tasks	All modalities tested	average accuracy	0.16				n/a				STM: 18/39; WM: 10/28; Other: 4/16
	b vs. s		children and adults	Verbal tasks	All modalities tested	average accuracy	0.44				0.66				STM: 14/25; WM: 9/22; Other: 8/18
	b vs. s		children and adults	Nonverbal tasks	All modalities tested	average accuracy	-0.15				-0.07			0.09	STM: 0/1; WM: 0/1; Other: 0/3
	b vs. s		children and adults	All tasks	Auditory	average accuracy	0.47				0.43			0.49	STM: 9/27; WM: 3/14; Other: 8/20
	b vs. s		children and adults	All tasks	Tactile	average accuracy	0.45				2.77			0.09	STM: 1/3; WM: 2/2; Other: 0/1
	b vs. s		children	Tasks matching for SES	Auditory	average accuracy	1.19				0.35			0.04	STM: 3/4; WM: 0/1; Other: 2/4
Note. b- blind; cb- congenitally blind; eb- early blind; lb- late blind; ob- older blind; os- older sighter; ps- partially blind; RT is reaction time (ms); s- sighted; st- short-term; tb- total blind; wm- working memory; yb- younger blind; ys- younger sighted. Span scores include effect sizes for combined forward and backward span scores. Interpret late blind averages cautiously as only one value is included. Interpret 3-back early bl															
Article notes:															
[a] Wyver & Markham (1998)	calculated based on conditions without articulatory suppression for all spans. Excluded from overall sample sizes due to not providing subsamples by blindness category.														
[b] Bathelt et al. (2018)	calculated based on partially sighted (moderate and severely visually impaired) participant average means and SEMs. Mean and SEM not provided for blind participants (n= 1).														
[c] Rindermann et al. 2020	Calculated D using working memory capacity score. Significance is based on independent samples t test. Authors failed to provide P value.														
[d] Bliss, Kujala, & Hamalaine (2004); ad	Significance for braille (blind) vs. tactile (sighted) comparison is based on independent samples t test. Authors failed to provide P value.														
[e] Raz et al. (2007)	Effect size based on session one values.														
[f] Rokem and Ahissar (2009); add lette	Calculated effect sizes for pseudoword span sequence lengths 3-5 under all conditions because they were visible; sequence lengths 1-2 were not.														
[g] Burton et al. (2010)	Significance for accuracy comparison is based on independent samples t test. Authors failed to provide P value.														

Table 1.1: Effect Size of Cohen’s D (Blind and Sighted Comparison)

Yet on tasks in which items are not verbalizable, blind participants lose their advantage. No group differences emerge when participants are asked to complete an n-back task using tones of various pitches (Park et al., 2011). Though blind adults do outperform sighted adults on recalling pseudowords heard in a quiet background, the same Blind and sighted adults recall lists of pseudowords equally well when heard with masking speech noise (cf. table 1.1; Rokem & Ahissar, 2009). Another counterexample is an episodic recognition memory study finding that compared to late blind and sighted participants, early blind adults recognized significantly more nonverbal but verbalizable environmental sounds from a list of previously heard sounds and foils (e`.g`. turning book pages and musical instruments Cornell Kärnekull, Arshamian, Nilsson, & Larsson, 2016; Röder & Rösler, 2003). Note that because these studies' sounds had semantic associations, participants may have attributed a verbal label to each sound unlike the asemantic content in Rokem and Ahissar (2009).

When evaluating STM or WM, similar null findings prevail if items are encoded using tactile stimuli. A nonverbal tactile vibratory n-back task found no evidence for an STM advantage in blindness (Burton, Sinclair, & Dixit, 2010). On this 1-back task, participants matched the current vibration frequency to the prior trial's frequency. Furthermore, no between-group differences were found on a 2-back WM task using asemantic braille dot patterns and differing voices speaking the same word (Gudi-Mindermann et al., 2018). Similarly, no differences were found among the same participants on n-back tasks regardless of whether content was verbal (i.e. word n-back) or nonverbal (i.e. pitch n-back using sinusoidal tones and spatial n-back using pure tones varying by location Park et al., 2011).

Comparing groups’ WM for verbal and nonverbalizable content is important to better understand what may contribute to the inconsistent WM findings. Though studies have compared participants who are blind and sighted on a variety of verbal and nonverbal memory tasks, results only focus on whether or not groups differ (Dormal et al., 2016; Park et al., 2011; Pigeon & Marin-Lamellet, 2015; Rokem & Ahissar, 2009). They fail to explicitly discuss whether the content type being memorized may influence group differences and instead primarily use verbalizable or phonological content such as assigning names and pseudo-words on nonverbal tasks (Ekstrom, 2018; Rokem & Ahissar, 2009). At least one study finds that while those who are blind outperform the sighted when encoding nonverbal but verbalizable items, their advantage over the sighted is even larger when semantically encoding items rather than attending to their loudness (Röder & Rösler, 2003). Together, these results suggest that people who are blind may need meaningful content for their advantage over the sighted to persist. Understanding if, and which, content types contribute to the memory differences may clarify which processes may explain the discrepant WM findings.

Impact of modality on WM

Visual WM in sighted individuals is better developed than their auditory memory (Frick, 1984) and their tactile memory (Bliss et al., 2004). This difference is believed to stem from sighted individuals relying on vision as their primary sense for obtaining information. In contrast, individuals who are blind recall more words in braille as opposed to heard information (Pring, 1988), demonstrating a dominance of tactile encoding.

Though we encode information using multiple senses for future recall, we have yet to understand how sighted individuals' memory compares to that of blind individuals when encoding information unimodally and comparing across modalities and participant groups. Although sighted participants have been tested using multiple modalities (Bliss et al., 2004; Frick, 1984; Gudi-Mindermann et al., 2018) as have blind participants (Bliss et al., 2004; Gudi-Mindermann et al., 2018; Pring, 1988), the evidence directly comparing both groups across multiple modalities (other than hearing) warrants more investigation to understand if memory differences exist per modality across groups, their magnitude, and the direction of the effect.

Understanding cross-modal between-group comparisons also warrants more exploration since the majority of studies comparing across modalities do so within-groups. In the case of blind individuals, previous work has found that occipital cortex activates for auditory, tactile, and memory-related tasks (for review, see Collignon, Voss, Lassonde, & Lepore, 2009). Evidence suggests blind and sighted children recognize more words read in braille and print, respectively, as compared to when listening to word list pairs during verbal STM and recognition memory experiments (Pring, 1988).

Few studies assessing performance across modalities among blind participants exist. Studies testing blind participants typically do so using audition in children (Bathelt et al., 2018; Hull & Mason, 1995; Withagen et al., 2013), adolescents (Ekstrom, 2018), and adults (Pigeon & Marin-Lamellet, 2015, 2017; Rokem & Ahissar, 2009). This may be because ensuring auditory stimuli are accessible to blind participants is easier than using tactile stimuli. Auditory stimuli require equipment common in most laboratories and involve less motion than actively touching stimuli, making it more ideal for other neuroimaging and neurophysiological studies. As a result of testing blind individuals unimodally, little evidence exists to address whether or not presentation modality influences performance differences.

Moreover, the few studies that compare crossmodally across groups vary with respect to design. For example, Bliss et al. (2004) uses a within-subject design among blind and sighted participants while varying the modalities (visual print letters among sighted, tactile print letters among everyone, and braille letters among blind) for an n-back task with a fixed number of levels. On the other hand, Gudi-Mindermann et al. (2018) trains blind and sighted participants on an n-back task using a between-subject design in which separate groups are tested using different modalities. This makes assessing the extent of memory differences more challenging due to lack of uniformity across designs.

Even less research questions braille’s impact on memory in blind individuals, leaving an open question regarding how braille impacts blind individuals’ STM and WM abilities. Braille appears to benefit blind individuals’ STM abilities when stimuli are verbal as compared to when using less familiar verbal material. Pring (1988) find that blind children recognize more words read in braille as compared to heard words, while Bliss et al. (2004) find blind adults score more accurately when performing an n-back task using braille as compared to when touching raised print letters, though accuracy differences across braille and raised print are nonsignificant. Considering the differing results for recalling braille vs. tactile letter stimuli, braille’s impact on memory relative to other modalities warrants more attention.

Though blind and sighted participants may have similar levels of familiarity with braille and print, braille takes longer to read than print (Wetzel & Knowlton, 2000). Yet Bliss et al. (2004) used the same interstimulus interval across braille and print, which may have contributed to finding no difference in performance between blind and sighted adults on a letter n-back task when tested in braille and print (cf. table 1.1).

This difference between groups across modalities suggests that modality, processing speed, and familiarity with the material being encoded may influence WM performance. To better understand the extent to which modality influences memory abilities among blind and sighted individuals, studying each group's memory cross-modally is needed. By testing memory performance using vision, audition, and braille in the same study as opposed to only two out of the three modalities, we may better understand how WM performance using vision in sighted adults is similar to or different from tactile WM performance using braille in blind adults, for example.

Matching for Demographic Differences

Evidence suggests that demographic factors such as age, education, and SES impact all individuals' WM abilities. From childhood through early adulthood, WM abilities improve, then decline with age (Hartshorne & Germine, 2015). WM also predicts one's academic achievement (Swanson & Alloway, 2012), which may be partly due to WM's role in reasoning and comprehending information. Education in turn influences one's SES level. Income and maternal education influence individuals' WM abilities, and a weak but significant correlation exists between income and children's WM (Hackman et al., 2014; Noble et al., 2015). Therefore, considering these factors when evaluating WM differences across groups is important to more carefully isolate the factors being manipulated.

Impact of SES

One often overlooked area when comparing memory of individuals who are blind and sighted is SES. SES can be operationalized objectively based on individuals' income and education, along with caregivers' education as applicable (Hackman et al., 2014; Sapolsky, 2004). SES may also be measured subjectively based on self-ratings of where one stands relative to others in society, which varies by culture and has health implications (Sapolsky, 2004). Moreover, parental education significantly and positively predicts children's WM performance in a longitudinal study (Hackman et al., 2014). Parental education influences their SES which in turn affects if, and how much, parents can afford resources to expose their children to educational opportunities outside academic settings to reinforce what they have learned, suggesting parental education needs to be considered in addition to participants' education (Hackman et al., 2014).

Individuals of low SES are also more likely to be diagnosed with visual impairments, partly due to unequal access to healthcare (Dandona & Dandona, 2001). Despite the documented SES trends for those who are blind and SES's impact on WM, few studies explicitly match for SES among groups. Most studies measuring WM differences across blind and sighted individuals account for some, though not all, of the following demographic characteristics in participants: age, class, education, gender, IQ, and musical training. Studies assessing children's memory differences have matched participants for age, gender, social class, and intelligence quotient (IQ Smits & Mommers, 1976). Interestingly, in studies in which IQ is being considered, IQ tests such as the Wechsler Intelligence scale for Children include scales that capture WM as part of the assessment(Keith, Fine, Taub, Reynolds, & Kranzler, 2006), so by matching for IQ, one may argue authors are somewhat matching for WM abilities.

Despite parental education influencing one’s WM performance, studies that consider demographic characteristics between blind and sighted participants typically only consider participants’ educational levels without considering parental education. Failing to account for SES using sensitive enough measures may also influence the extent to which blindness accounts for the difference or lack thereof depending on matching criteria. Though maternal education is only one of several factors predicting WM performance (Hackman et al., 2014), taking it into account when measuring WM differences in samples of blind and sighted children such as Swanson and Luxenberg (2009)‘s sample is particularly relevant and may partly explain their null results for between-group differences on backward digit span tasks.

In the few studies of blind and sighted individuals mentioning SES, a contrast in results exists that may depend on whether or not participants were matched for SES. For example, in a study of STM and WM in blind and sighted children ranging from low to high social class and matched only for age, gender, and IQ, significant differences were found on both forward and backward digit span tasks (Smits & Mommers, 1976). However, a study of congenitally blind and sighted children matched for middle class SES, age, verbal intelligence, and gender found group differences only on STM ability for forward digit and word span tasks (Swanson & Luxenberg, 2009). In this study, no group differences were found for the more intensive WM measures, including a backward digit span task and a recall task involving interference.

The demographic factors studies match participants on may influence whether or not authors find group differences between blind and sighted participants’ memory performance. In studies that do match for at minimum age and education, some find that participants who are blind outperform the sighted on STM (Raz et al., 2007; Rokem & Ahissar, 2009), working (Occelli et al., 2017), and long-term memory tasks (Raz et al., 2007).

In the case of studies that find mixed or no WM differences between blind and sighted adults, they match for age (Bliss et al., 2004; Gudi-Mindermann et al., 2018; Park et al., 2011), as well as gender (Park et al., 2011) and IQ (Gudi-Mindermann et al., 2018). Bliss et al. (2004)'s design was effective in that they found a negative effect of load on WM performance regardless of group. Had they matched for other factors that influence WM such as maternal and participant education, more between-group results may have emerged. Similarly, Gudi-Mindermann et al. (2018) were also effective in replicating the finding that WM training improves WM regardless of group, though no between-group differences were found. Park et al. (2011) may have also found null between-group results on all forms of n-back tested due to failing to match for participant or maternal education. However, were income or any form of education considered, the above studies may have found stronger between-group differences since participant and maternal education affect one's WM abilities beginning as early as childhood (Hackman, Gallop, Evans, & Farah, 2015; Swanson & Alloway, 2012). The more of these qualities are accounted for per group, the more certain we can be that WM results are due to consequences of visual deprivation and less so to other demographic factors such as income.

Though considering all demographic and socioeconomic factors associated with WM is less feasible, prioritizing those that have been documented to influence it (i.e., maternal education Hackman et al., 2014) will allow us to more confidently determine the conditions under which these memory differences manifest themselves. For example, a study of congenitally blind and sighted adults matched only for age and gender found no differences in STM or WM between participants (Castronovo & Delvenne, 2013). However, authors failed to match for education, a variable known to impact memory performance (Swanson & Alloway, 2012). In contrast, STM and WM studies that do match for education in blind and sighted participants have found between-group differences (Occelli et al., 2017; Raz et al., 2007). Therefore, not only does the question of why said differences occur remain open, but the conclusions we can draw from studies that describe participants to a lesser extent are limited, which may influence effects' magnitude and direction.

Hypotheses and Research Questions

We consider the following variables to better understand if, and what, contributes to WM differences in those who are blind and sighted. What influence do age of blindness onset, verbal and nonverbal stimuli, modality, and SES characteristics play in blind and sighted participants' memory performance differences? Addressing how these qualities influence between-group memory differences will shed light on the extent to which each contributes to said differences and may help us begin to clarify why mixed findings exist between groups based on which factors studies consider.

Methods

To identify candidate articles, we searched for peer-reviewed articles in Google Scholar that met the following criteria. Articles were quantitative, identified the modality in use for encoding information, and tested individuals who are blind and sighted. To be included, articles also needed to assess STM, WM, or both in children or adults who are blind and sighted. Any STM or WM task could be used as long as the stimuli were verbal (i.e., letters etc.), nonverbal but verbalizable (i.e., pseudowords or environmental sounds), or nonverbalizable (i.e., vibrations or tones).

The following search terms were used to search PsycInfo database: “blind" OR "visually impaired" AND "sighted” AND “memory” OR “short-term memory” OR “working memory” OR “verbal” OR “nonverbal" NOT "schizophrenia" NOT "intellectual disability" NOT "learning disability" NOT "delay" NOT "validity" NOT "aphasia.: The original list contained a grand total of 171,928 articles, of which 171,907 were excluded.

Articles that failed to report relevant statistics of the behavioral results required to compute the Cohen’s D effect size were excluded (see Hull & Mason, 1995; Jonides, Kahn, & Rozin, 1975). Articles also needed to either identify if group differences were found or provide enough descriptives to calculate if differences were significant (cf. see table 1.1). Articles were excluded from the review if participants had additional disabilities diagnosed other than a form of visual impairment such as a neurological disorder. Brain-related, nonbehavioral results were also excluded, such as fMRI, EEG, TMS, ETC. If articles specified matching for or controlling for characteristics between groups, variables that were either controlled for or matched between participants were included in analysis as possible explanations for group differences, if any. The final list was comprised of 21 articles published between 1968-2020.

Measures.

We used the reported descriptive statistics to calculate effect sizes (Cohen’s D = $(\text{mean}_2 - \text{mean}_1)/ \sqrt{((\text{sd}1^2+\text{sd}2^2)/2)}$) of STM and WM differences between blind and sighted participants. Significance levels of between-group differences were also calculated if needed for vote counting (Bushman & Wang, 2009). Vote counting was calculated for STM, WM, and other memory comparisons. Vote counting consisted of the proportion of significant between-group comparisons over the total number of comparisons irrespective of their significance. Vote counting proportions were calculated separately per memory category. STM tasks were comprised of forward span tasks, span tasks in which forward and backward spans were provided as a single composite score, 0-back, and 1-back scores. Span and 0-back tasks operationalized STM due to only requiring recalling information without manipulating any; 1-backs were used due to only needing to recall the current item with no updating or interference component. WM measures were operationalized using backward spans, 2-back and 3-back scores due to tasks involving greater cognitive demands such as updating and reversing item order. WM measures consisted of backward spans, 2-back and 3-back scores. When unclear of the form of memory being used in articles' task(s), they were categorized as STM or WM according to authors' classification when provided. Effect size averages for STM and WM tasks and vote counting results are shown in table 1.1. Effect sizes for any STM or WM scores that did not fall into the predefined STM and WM categories were averaged separately (i.e., complex span tasks involving interference, categorizing words, sentence spans).

Results

Influence of Blindness Onset

On memory tasks that were not explicitly classified as STM or WM, children who are blind showed an advantage that is trending toward medium (d = 0.44) with 3/7 comparisons favoring blind over sighted individuals (cf. table 1.1). Blind children exhibit a large STM advantage over the sighted (d = 0.87), with 4/7 comparisons significantly favoring blind over sighted individuals. On WM tasks, blind children also exhibit an advantage over sighted children that is trending toward large (d = 0.76), with 1/2 comparisons being significant.

When measuring STM differences in blind and partially sighted participants as compared to sighted participants, the effect size is close to zero (d = 0.04) with nonsignificant differences between groups, suggesting visual impairment severity impacts the magnitude of the advantage.

Blind people's advantage over sighted individuals continues into adulthood, though to a lesser extent. When comparing blind and sighted adults on STM tasks regardless of onset, blind individuals exhibit a small STM advantage over sighted ones (d = 0.37) with 9/22 significant comparisons. The difference increases when considering blindness onset, with congenitally and early blind participants showing an advantage over the sighted that is trending toward large on STM tasks (d = 0.68) with 3/9 significant comparisons. Late blind as compared to sighted participants show a different trend on STM tasks in which the sighted show a small advantage over the late blind participants (d = -0.13), though only 1/3 comparisons find a significant group difference.

With respect to WM, both early and late blind adults show a medium advantage over the sighted (d = 0.58), with 8/20 significant comparisons. In the case of congenitally and early blind adults as compared to sighted adults, the advantage for blind individuals slightly increases (d = 0.60) with 1/6 significant comparisons. Again, the advantage in blind over sighted individuals decreases when only considering late blind and sighted participants, who show an advantage trending toward medium (d = 0.40) though all comparisons were nonsignificant.

Impact of Verbal and Nonverbal Stimuli

Across the articles that included verbal STM findings, blind participants showed an advantage over the sighted that trended toward medium (d = 0.44) and were significant for 14/35 comparisons. The blind samples' medium advantage over the sighted increases on verbal WM tasks (d = 0.66) and was significant on 9/22 comparisons.

In contrast, on nonverbal STM results, the sighted showed a slight advantage over blind persons (d = -0.15), though the one comparison was nonsignificant. Sighted individuals maintain their slight advantage over blind individuals on nonverbal WM tasks (d = -0.07; cf. table 1.1), though the one comparison was nonsignificant.

Impact of Modality on WM

Effect sizes were not analyzed for modality due to only two included articles manipulating modality among participants (Bliss et al., 2004; Gudi-Mindermann et al., 2018), and only one found significant differences (Bliss et al., 2004).

Impact of SES on WM

Of the four tasks that took SES factors relating to income in to account such as social class status, blind participants exhibited a large advantage over the sighted on STM tasks (d = 1.19) with 3/4 significant comparisons. Blind participants' advantage over the sighted decreased to an effect trending toward medium on WM tasks (d = 0.35) with the one comparison being nonsignificant.

Discussion

This review aimed to clarify how factors such as blindness onset, stimulus type, encoding modality, and demographic characteristics may explain the mixed existing STM and WM results among humans who are blind and sighted. Specifically, we sought to systematically compare across studies using Cohen's D effect size as a standardized measure to understand the magnitude and direction of the between-group differences contingent upon which demographic factors were considered. We also carefully investigated study design procedures such as if, and what, demographic and socioeconomic factors were taken in to account when matching participants as possible explanations for the mixed findings, for characteristics including age and education influence WM abilities (Hartshorne & Germine, 2015; Swanson & Alloway, 2012). Finally, we provide study design recommendations for future studies to incorporate.

Influence of Blindness Onset

Our analysis supports the claim that the memory advantage in blind humans begins during childhood, showing a large advantage in blind over sighted on STM tasks,. Since over half of STM comparisons were significant, this proportion suggests that blind individuals' advantage may refine itself over development (cf. table 1.1. STM's lower cognitive demand may facilitate blind children having a large advantage over the sighted as a result of blind individuals recalling items in serial order more frequently as compared to the sighted (Cowan, 2008; Raz et al., 2007).

On WM tasks, blind children’s advantage over the sighted is trending toward large, suggesting blind children’s WM advantage over the sighted may be smaller as compared to their STM advantage because WM is more cognitively demanding. Since WM is still developing during childhood, children’s abilities to manipulate and update information may be less refined as they continue developing their prefrontal cortex (Tsujimoto, 2008), leading to smaller between-group differences. However, these results warrant careful interpretation as only two comparisons were included.

Adults who are blind show smaller STM advantages over the sighted. When comparing all adults who are blind and sighted on STM tasks, blind individuals show a small STM advantage over the sighted, meaning that perhaps including all blind participants regardless of onset may have lowered results. When considering blindness onset, the difference between groups increases, with congenitally and early blind participants showing an above-medium advantage over the sighted on STM tasks. In contrast, sighted participants’ small advantage over late blind participants suggests the lower cognitive demand of STM tasks may allow the sighted to outperform blind individuals, though this needs to be interpreted cautiously since the majority of comparisons between these groups were nonsignificant. The significant advantage in studies of congenitally and early blind participants as compared to those of late blind and sighted participants suggest that though the late blind can develop an advantage, it is weaker than in those who became blind sooner (Dormal et al., 2016). Therefore, blindness onset may influence the magnitude of the advantage in blind persons. The greatest between-group differences appear when only including those who became blind early in life.

With respect to WM, all blind adults regardless of onset show a medium advantage over the sighted. Congenitally and early blind adults as compared to sighted adults show a very slight increase in their WM performance relative to all blind and sighted participants regardless of onset. When considering late blind and sighted participants, the late blind persons' advantage over sighted individuals decreases with a trend toward medium. Therefore, though blind populations may develop a WM advantage over the sighted despite later vision loss, their advantage may be less developed as compared to those who lose their sight sooner.

When recalling items in WM, strategies that blind samples use such as chaining items in space and time, along with recalling items by ordinal position may be less applicable due to WM involving manipulation, leading to smaller WM differences despite blind individuals showing improved performance for serial recall as compared to sighted participants (Raz et al., 2007). In addition to considering blindness onset's role in between-group memory differences in future research, visual impairment severity's impact on memory is also an open question, as it may also impact if, and the extent to which, memory differences per group are found. For example, the much smaller STM advantage found in visually impaired over sighted children on Wyver and Markham (1998)'s tasks suggests visual impairment severity impacts the magnitude of the advantage.

Impact of Verbal and Nonverbal Stimuli

In terms of verbal memory advantages, the trend toward a larger advantage for STM over WM in blind relative to sighted individuals continues. This may be because the STM tasks used in these studies involved recalling information in serial order, and those who are blind have been shown to have an advantage for both recalling verbal information and for doing so in serial order (Raz et al., 2007). However, considering that under half of included between-group comparisons were significantly different, other factors such as blindness onset and demographic characteristics known to influence STM need to be considered to better understand what explains these group differences.

From highest to lowest, the proportion of significant verbal memory comparisons occurred for STM, other memory tasks, and WM, respectively. For verbal STM, participants who are blind collectively earned an advantage slightly above medium. Though this advantage persists for verbal WM tasks, it is slightly smaller than the STM advantage, suggesting that WM tasks were adequately taxing as compared to the STM tasks.

On nonverbal memory tasks, the result patterns differ in that the sighted outperform blind individuals on nonverbal STM tasks, whereas participants who are blind only have an advantage over the sighted on nonverbal WM tasks. However, nonverbal results warrant careful interpretation in that of the two nonverbal STM tasks included, only one is significant, and on the nonverbal WM tasks, none are significant despite blind persons' medium advantage. More research is needed to understand if the blindness memory advantage is specific to verbal or nonverbal information, as well as why this advantage may occur. Of the tasks included in this analysis, only Park et al. (2011) directly compares verbal to nonverbal WM within-groups, so more work that directly compares verbal to nonverbal memory performance in both groups is needed to understand what may contribute to these differences and potentially replicate the pattern of significant and nonsignificant verbal and nonverbal results, respectively. One potential explanation for the blind individuals' higher performance on verbal as compared to nonverbal memory tasks is that verbal memory involves cognitive mediation while nonverbal memory involves only perception, possibly making nonverbal tasks less taxing than verbal tasks for sighted participants depending on design. Sighted participants' higher performance on nonverbal

STM tasks may contribute to the smaller between-group differences relative to blind individuals. These results suggest that while blind participants do have a memory advantage over the sighted, it is greatest for verbal over nonverbal memory tasks.

Impact of Modality on WM

Modality results are interpreted cautiously due to the majority of articles utilizing auditory measures, and only three incorporate some form of a tactile measure. The three tasks assessing tactile WM vary with respect to stimulus type, the measure being used, and timing, thus making comparing more difficult. Of the three that include tactile measures, only Bliss et al. (2004) find significant differences between blind and sighted on one through 3-back tasks using tactile print-shaped letters. The significant differences found on all n-back levels except a 0-back suggests updating may be needed for group differences to manifest themselves. Group differences may have been found due to using less transient stimuli—static letters presented in a fixed location for a fixed amount of time, which may have facilitated encoding and comparing letters (Bliss et al., 2004). Disentangling the specific influence of modality from that of other confounding variables is needed to better understand the extent to which modality influences WM performance in blind relative to sighted individuals.

Of the tactile studies analyzed, the majority find nonsignificant between-group differences. Stimuli may influence participants performance. One study measured participants' n-back accuracy before and after training using alternating tactile and auditory stimuli (Gudi-Mindermann et al., 2018). In contrast, training used either all tactile, all auditory, or alternating versions of each condition between-groups. Therefore, the training trials and pre and posttraining trial procedures were inconsistent and may have contributed to the nonsignificant between-group differences. Furthermore, their tactile task is more transient due to using moving braille dots that varied in terms of direction and finger feeling them, thus requiring more attention. To complicate this interpretation further, the additional tactile task included in analyses contained a spatial component—a Corsi block task whose design differs from a nonspatial n-back's, making comparing less possible (Occelli et al., 2017). Inconsistent designs limit the extent to which we can draw robust conclusions about how much modality contributes to memory differences. Regardless, nonsignificant between-group differences were found on both tasks, leaving modality's impact on WM in blind and sighted individuals as an open question for future research.

Role of SES on Memory Differences

Evidence suggests individuals' SES impacts their WM abilities, in part due to SES measures such as maternal education and income affecting individuals' access to resources (Hackman et al., 2014). Despite the role of SES on WM, only two of the included studies carefully assessed SES measures such as class status in children (Smits & Mommers, 1976; Swanson & Luxenberg, 2009). Though blind individuals maintain their superior STM and WM advantage relative to the sighted across studies that do and do not match for SES, the difference in performance patterns vary depending on the form of memory being measured and on whether SES is considered. That is, blind participants' STM advantage over sighted participants is larger across studies that match for SES as compared to all included studies of children. One possible explanation is that STM tasks are less taxing, so unequal SES may have less of a negative impact on performance.

In contrast, blind individuals exhibit a larger WM advantage over the sighted when considering all studies of children as compared to those that match for SES. This contrast suggests that considering SES may indeed decrease the magnitude of the WM difference, possibly due to WM tasks being more demanding and to the positive relationship between SES and WM in children (Noble et al., 2015). Therefore, demographic factors that influence WM such as SES need to be considered to better understand how much these factors contribute to WM differences between blind and sighted relative to the impact of blindness itself. To our knowledge, the only SES measure considered in STM and WM studies of blind and sighted adults is education (Occelli et al., 2017; Raz et al., 2007; Rokem & Ahissar, 2009). No included studies of STM and WM in blind and sighted adults consider other SES measures such as income despite its important role, leaving the impact of SES on memory differences in these populations as an open question.

Conclusions

This review finds that blindness onset and whether stimuli are verbal or nonverbal contributes to between-group differences in memory performance between individuals who are blind and sighted. Between-group differences are most pronounced between congenitally and early blind participants as compared to sighted individuals. Differences in between-group comparisons are more evident on tasks using verbal as opposed to nonverbal stimuli. The majority of studies assessed here used verbal as compared to nonverbal stimuli (75/81 verbal tasks and 6/81 nonverbal tasks), again suggesting a need to not only compare memory across blind and sighted individuals as these studies do, but also to compare their performance across stimuli to gain a clearer understanding of whether superiority for individuals who are blind on certain memory tasks is dependent on the stimulus type being tested. As can be seen in table 1.1, the majority of comparisons employed in previous work (50/66) test individuals in the auditory modality. Therefore, less evidence exists to evaluate other modalities' influence on STM and WM abilities, so more work testing memory unimodally and cross-modally is needed to assess memory performance across groups and modalities. SES appears to affect group differences more on STM as compared to WM tasks, suggesting the WM advantage in blind individuals may be smaller than previously thought. Due to maternal education and income being associated with children's WM, considering both would allow for a more accurate between-group comparison of WM revealing significant differences that may otherwise not be found. More work that assesses the roles of verbal and nonverbal stimuli, SES characteristics, and modality is needed to understand what may contribute to the WM findings identified thus far. The following two studies address the roles of verbal and nonverbal stimuli, modality, and SES in more depth.

Chapter 2

Superior Verbal over Nonverbal Memory in Congenital Blindness

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Abstract

Blind individuals use WM extensively to complete tasks that sighted individuals would achieve visually (e.g. using verbal descriptions of environmental sounds for navigation). Researchers have speculated that daily extensive use of WM in blindness results in larger memory capacity and improved efficiency in WM manipulation. In this study, we evaluate whether these benefits extend to WM resilience in the context of interfering verbal tasks and to nonverbal recognition memory tasks in which items cannot be easily labeled linguistically. We found congenitally blind participants recalled more letters as compared to age and education-matched sighted participants in serial order, reverse order, and on a complex letter span in which intervening equations precluded rehearsal. On a verbal recognition task, blind participants again outperformed the sighted when distinguishing between previously heard lists of letters and lists containing foils. Critically, on a matched nonverbal recognition memory task using lists of complex, nonmeaningful sounds, the difference between blind and sighted participants was eliminated.

Overall, our results are evidence that blind individuals’ memory advantage over the sighted may be specific to linguistic information, an example of experience-dependent neuroplasticity in cognitive systems supporting verbal memory.

Keywords: Visual deprivation, congenitally blind, adult, verbal, nonverbal, memory, WM, 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 non-visual 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; Burton et al., 2012; Kim, Elli, & Bedny, 2019). Accumulating evidence suggests that blindness enhances some linguistic abilities, perhaps as a result of heavy reliance on language as a source of information. People born blind learn to understand speeded speech using synthesized voices (Jacko, 2011), show speeded lexical access (Röder, Demuth, Streb, & Rösler, 2003; Röder, Rösler, & Neville, 2000), and outperform the sighted when answering comprehension questions about grammatically complex sentences (Loiotile, Omaki, & Bedny, 2019).

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 (four seconds Occelli et al., 2017; Raz et al., 2007; Rokem & Ahissar, 2009; Smits & Mommers, 1976; Stankov & Spilsbury, 1978; Tillman & Bashaw, 1968; Withagen et al., 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). Blindness-related memory advantages have been documented as early as six years of age (Hull & Mason, 1995).

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; Withagen et al., 2013). One study found superior performance on n-back tasks with raised tactile letters at intermediate load levels (Bliss et al., 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 et al., 2016). One study found that 10-year-old blind children outperform sighted children on a listening span task in which individuals recall sentence's' last words while also answering whether each sentence is true or false (Withagen et al., 2013). In another study, blind adults better remembered sentence-final words in an incidental encoding paradigm with 80 sentences (Röder et al., 2001).

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 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 improve 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 WM for linguistic material (e`.g`. Christoffels, De Groot, & Kroll, 2006), and expert chess players show superior memory for chess configurations (Chase & Simon, 1973; for review, see Ericsson & Lehmann, 1996). Therefore, verbal memory in people who are blind might selectively improve.

Nonverbal Memory in Blind and Sighted

In contrast to the evidence that blind individuals outperform the sighted on a range of verbal memory tasks, the evidence on nonverbal memory tasks is decidedly more mixed. 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 et al., 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 & Rösler, 2003). Interestingly, Röder and Rösler (2003) also found that the advantage among people born blind was more pronounced with a semantic as compared to a perceptual encoding strategy. 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 listen to verbal stimuli but remembered nonverbal information. In this study, blind and sighted individuals performed with equal accuracy when listening to pseudowords 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; 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; 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 tend to find no advantages among people who are blind (Gudi-Mindermann et al., 2018).

Motivating the Study

The available evidence, while suggestive, falls short of distinguishing between the verbal memory and general memory advantage hypotheses in blindness. 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, however, 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). 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. 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. 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 2.1 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 2.2 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 non-verbal 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.

Math equations consisted 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. All participants in both groups were presented with the same equations in the same order. 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 no more than 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 X standard deviations 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 non-verbal sounds (500 msec) followed by a , 400 msec 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 400ms 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 no more than 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 2.1: 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 2.2: Average Woodcock-Johnson III Scores per group. Group means and standard deviations for task performance.

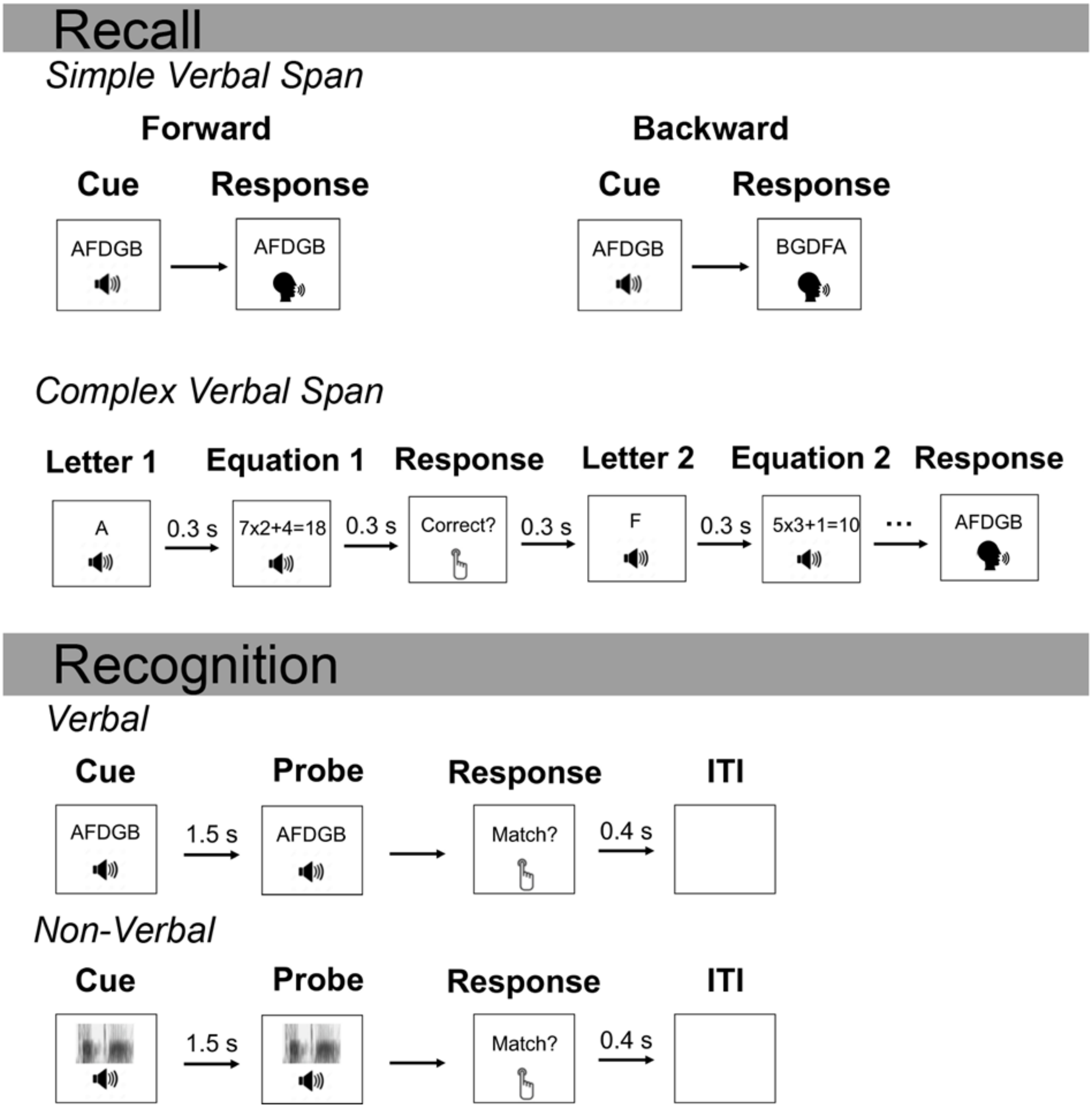

Figure 2.1: Tasks Recall

Participants repeated sequences of letters presented in an audio format. For forward recall, the list was repeated in the same order as presented, but for backward recall, the opposite order as presented. During complex recall, participants determine 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 non-verbal task, the list consisted of non-verbal 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 Non-Verbal

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 As a result of task difficulty during piloting. Therefore, lower load levels were analyzed for the nonverbal task compared to the verbal task.

Results

Experiment 1: Recall in Simple Verbal Span Task, Forward and Backward

Individuals who are blind showed enhanced STM 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 2.2a), 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, manipulating load affected individuals who are blind less (group X load interaction, $F(7, 273) = 3.62$, $p < .001$). By contrast, manipulating 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, $F(1, 273) = 76.09$, $p < .001$).

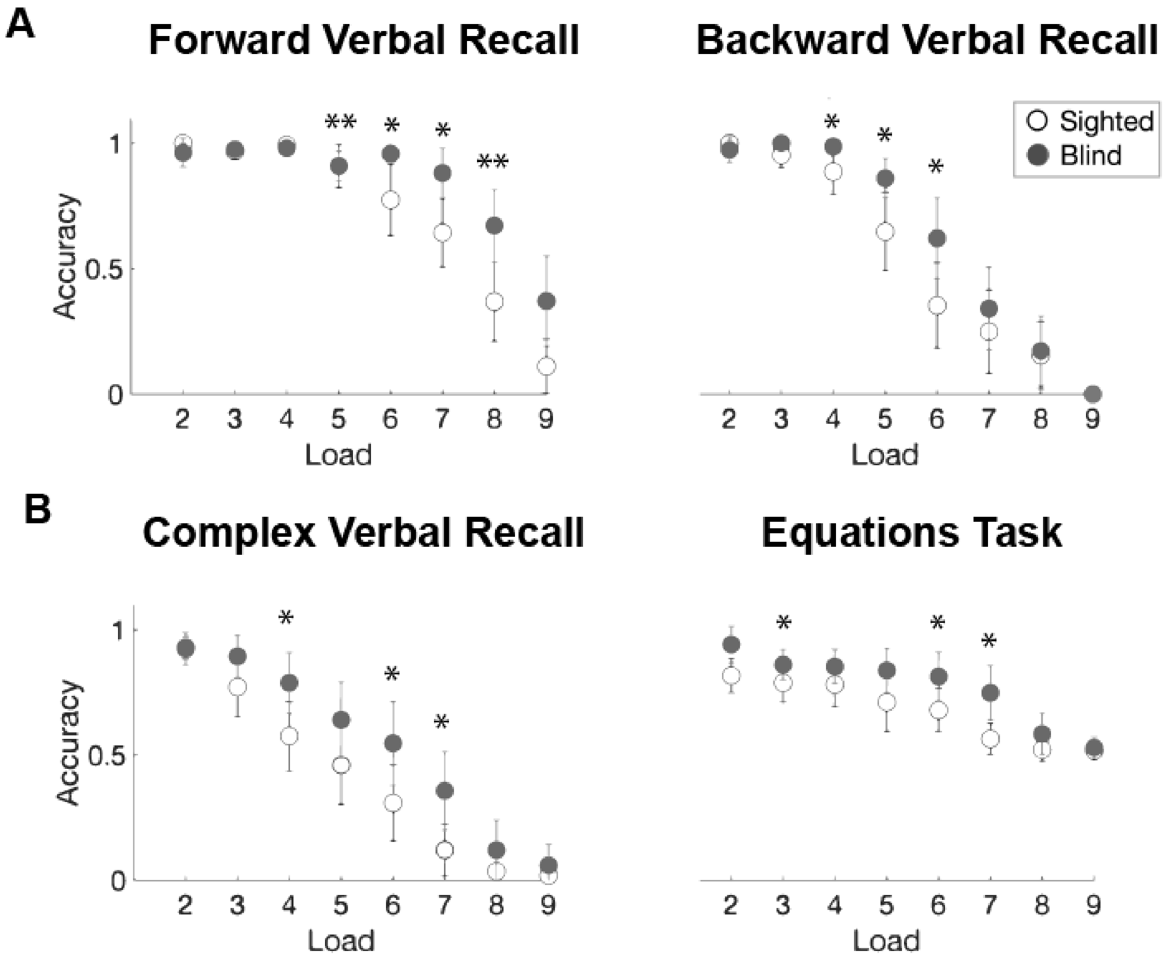

Figure 2.2: Verbal Recall Performance

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 STM recall in the context of interference (with math equations) in 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 2.2b; 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 2.2).

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 2.2b; 2 x 8 group-by-load ANOVA group, F(1, 39) = 6.610, p < .05). Increasing load in the concurrent letter-WM task negatively impacted both groups' performance on the equations task (load, F(7, 273) = 67.13, p < .001).

Experiment 3: Verbal and Non-Verbal 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 2.3a; 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 non-verbal 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 non-verbal task, (F(1,40) = 3.82, $p < .05$). Furthermore, in the non-verbal 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 non-verbal task (task X load, F(3, 120) = 7.16, $p < .001$).

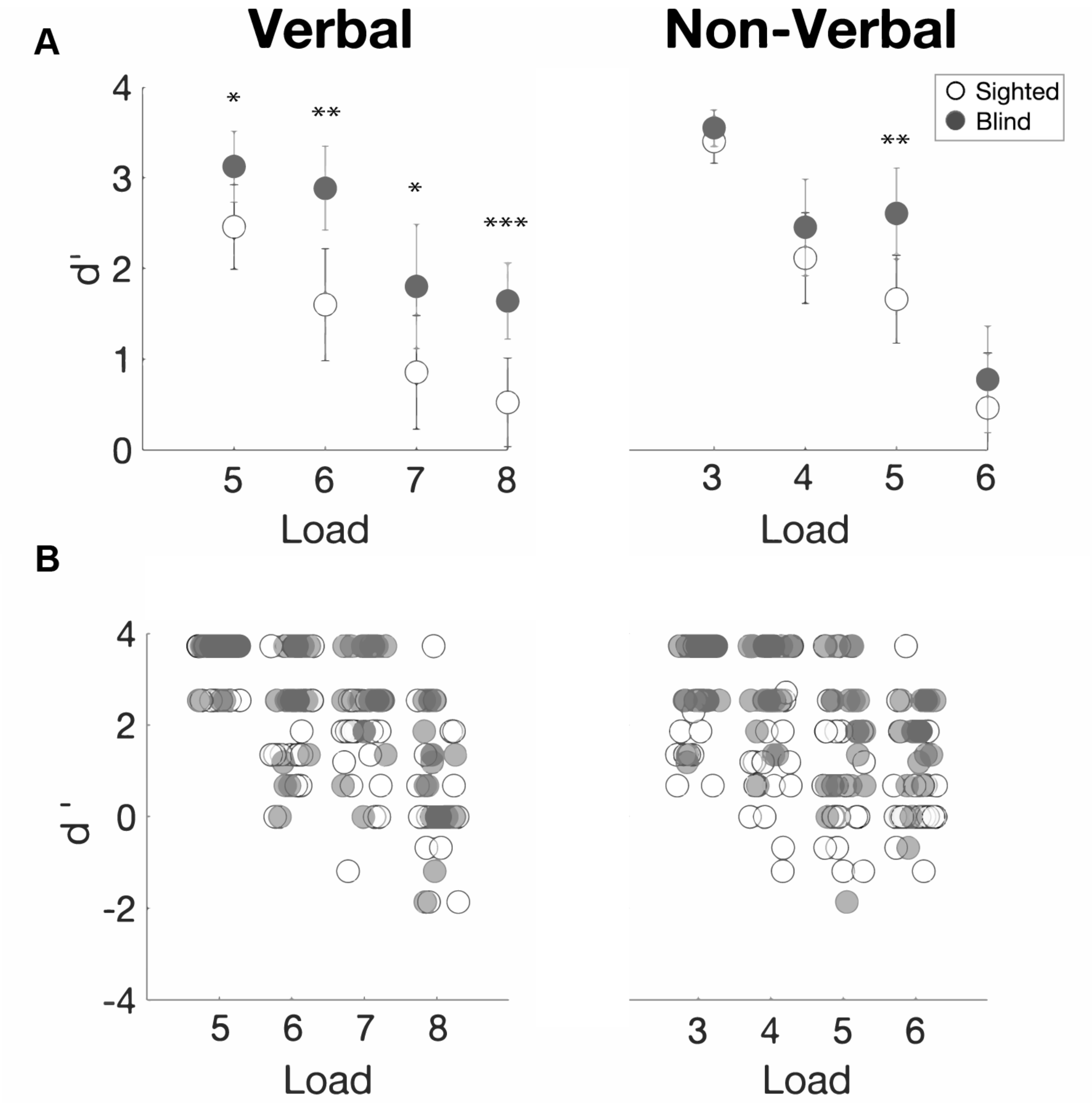

Figure 2.3: Recognition Performance

Performance on recognition tasks. A) Average d’ per load for each group is shown for verbal and non-verbal 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 correct letters in the correct order on forward, backward, and complex letter 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 remembered 13% more letters correctly. 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 current observation of larger memory advantages among people born blind for verbal material is consistent with a number of prior studies. Occelli et al. (2017) reported that blind participants outperformed the sighted on verbal but not spatial memory tasks. Specifically, blind participants outperform sighted ones on a backward digit span task and 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 extend these results by showing that the verbal nonverbal memory dissociation in blindness is observed even when the nonverbal task is nonspatial. The current results are also consistent with evidence that better performance using nonverbal sounds or tactile stimuli in people born blind appears to be related to verbalizability. Prior studies find blind individuals recognize more verbalizable sounds (e.g. sounds of musical instruments or of turning book pages) than sighted participants (Cornell Kärnekull et al., 2016; Röder & Rösler, 2003). In contrast, in the current study and in other work using non-verbalizable stimuli, blindness related advantages are absent (e`.g`. n-back tasks matching vibrations and voices Burton et al., 2010; Gudi-Mindermann et al., 2018). 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 and in prior work, 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 & Rösler, 2003). On a long-term memory task, blind participants recognized more verbalizable sounds than sighted participants after completing an 8-9 minute verbal fluency task (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). This study suggests that strategic rehearsal and encoding are not required for the blindness-related verbal memory advantage. Together, the available evidence suggests memory advantages in blindness are likely unrelated to more efficient rehearsal strategies for verbal information per se.

Rather, we hypothesize that blind individuals' verbal memory advantages reflect a genuine 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).

Cross-Modal Reorganization and Verbal Memory

An intriguing question for future work to resolve is whether enhanced verbal memory in blindness is related to 'visual' cortex plasticity or whether instead plasticity in classic fronto-parietal and medial temporal memory systems mediate the improvement (Amedi et al., 2003; Klingberg, 2010). People who are blind 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; Röder, Stock, Bien, Neville, & Rösler, 2002). Compared to sighted participants, those who are early blind also exhibit greater functional connectivity between left occipital cortex and frontal language areas when comprehending sentences as compared to a nonlinguistic control task using backward speech (Bedny et al., 2012; Deen, Saxe, & Bedny, 2015; Liu et al., 2007; Watkins et al., 2012). Particularly relevant to the current study, people who are blind activate 'visual' cortices when retrieving words from long -term memory, and the degree of activation in 'visual' cortex during encoding predicts 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).

Note, however, that ‘visual’ cortices are also involved in some non-linguistic tasks in blindness (e.g. Collignon, Renier, Bruyer, Tranduy, & Veraart, 2006). Different subsets of ‘visual’ cortex respond to linguistic and nonlinguistic tasks (e.g. Abboud & Cohen, 2019; Kanjlia, Lane, Feigenson, & Bedny, 2016). Whether and under what circumstances visual cortices participate in regarding nonverbal memory in blindness is not clear. One study found no occipital effects in blindness when comparing a 1-back task to an amplitude change detection task with vibro-tactile stimuli (Burton et al., 2010). By contrast, another study found larger responses to 2-back than 0-back tasks in occipital cortices with words, sounds, and sound locations (Park et al., 2011). Neither of these studies manipulated load parametrically, making interpreting findings complex. Two recent studies found that in blind but not sighted participants, nonverbal memory training incorporated occipital areas into WM networks, although no occipital responses were observed prior to training (Gudi-Mindermann et al., 2018; Rimmele, Gudi-Mindermann, Nolte, Roeder, & Engel, 2019). Neither of these studies observed memory advantages in the blind group either before or after training. Thus, occipital activation does not always result in behavioral benefits. Whether verbal memory advantages in particular 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.

Chapter 3

Perks of blindness: Enhanced Working Memory in Blind over Sighted Adults

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Abstract

Blind individuals commonly use memory-based strategies for situations in which sighted individuals use vision (i.e. finding items). These daily demands may serve as training to promote improved memory capacity, both for effectively maintaining information and for cognitively manipulating in WM. We therefore investigated whether visual deprivation impacts STM and WM abilities and how these abilities interact with the sensory modality by which information is encoded. We found blind adults recalled more items in an STM task than sighted participants, and this difference was more pronounced for items that were heard versus read in braille or seen, respectively. Blind participants also performed more accurately on an n-back task, but this group difference only appeared when SES factors were equated across the groups. We conclude experience-dependent plasticity is associated with improved WM functions.

Keywords: Visual deprivation, blindness, socioeconomic status, short-term memory, working memory

Introduction

Individuals who are blind must extensively rely on nonvisual memory strategies to complete everyday tasks that sighted individuals typically accomplish visually. When navigating, individuals who are blind utilize their WM to orient using auditory cues, while, for example, maintaining conversation (Raz et al., 2007; Saerberg, 2010). Those who are blind also rely on serial order and position to distinguish items from one another that can only be distinguished visually (e.g., different flavored yogurt in identical sealed containers differentiated solely by labels; Raz et al., 2007).

We hypothesize that individuals' reliance on memory may result in unique, practice-related benefits, illustrating experience-dependent plasticity of memory systems. The idea that individuals with congenital and acquired visual impairments experience plasticity in sensory systems is recognized in the literature, yet relatively little is known about how memory systems adapt to visual deprivation (for a review, see Bedny & Saxe, 2012). Previous STM and WM studies of children and adults who are blind have found mixed results. For example, several studies have documented that children who are blind recall significantly more digits in serial order on span tasks as compared to sighted individuals (Hull & Mason, 1995; Smits & Mommers, 1976; Swanson & Luxenberg, 2009; Tillman & Bashaw, 1968; Withagen et al., 2013). Children who are blind also outperform sighted individuals when asked to recall items in reverse order, an added cognitive manipulation (Hull & Mason, 1995; Smits & Mommers, 1976; Tillman & Bashaw, 1968; Withagen et al., 2013). In contrast, other studies find no group differences on simple STM or WM tasks (Bathelt et al., 2018; Ekstrom, 2018; Wyver & Markham, 1998).

Similar mixed findings exist in adults. Some find group differences on recalling items serially and in reverse (Bottini et al., 2016; Occelli et al., 2017; Pigeon & Marin-Lamellet, 2017; Rokem & Ahissar, 2009), particularly as the number of items to serially recall increases (Raz et al., 2007). Other studies find no performance differences in adults on simple STM or WM tasks (Castronovo & Delvenne, 2013; Pigeon & Marin-Lamellet, 2015; Rokem & Ahissar, 2009). Reasons for such discrepant findings remain unknown.

One important consideration may be that encoding modality may influence how well experimental items are encoded, with information being recalled more accurately when using more dominant modalities. Sighted adults and children have demonstrated differences in modalities used to encode information, as shown by their improved recall for items read visually as compared to heard (Frick, 1984; Pring, 1988). Presumably, encoding information through non-dominant modalities imposes higher cognitive loads, with the consequence of reducing memory performance. Better recall through the visual modality, which is used most frequently, may reflect the observer's ability to actively explore information visually at a self-guided pace (Klatzky, Marston, Giudice, Golledge, & Loomis, 2006), the tendency for visual information to persist for longer time durations than heard information, and the differences in how readily information can be verbalized, which is faster for visual information as compared to oral information in sighted individuals (Frick, 1984).

The encoding modality in use among blind individuals may also impact retrieval. Individuals who are blind commonly use text-to-speech software to access digital information

(Jacko, 2011). Text-to-speech is a passive form of transmitting information that does not readily allow for controlled exploration of previously heard material. When encoding information using text-to-speech, individuals must actively commit the contents to memory without the benefit of self-pacing. Therefore, they rely on auditory WM as they manipulate relevant details and update the content of their WM as information is read aloud. Overall, studies show that synthesized speech places greater encoding demands on individuals, particularly for more complex material (Freitas & Kouroupetroglou, 2008; Ralston, Pisoni, Lively, Greene, & Mullennix, 1991). Such demands may lead to blind individuals extensively developing their WM for auditory content to inform themselves of and respond to relevant information. we are less clear about how well blind adults' auditory WM abilities compare to WM when using other modalities such as touch.

Alternatively, blind individuals may exhibit a WM advantage over the sighted that generalizes to both auditory and tactile stimuli. Children who are blind and literate in braille recall more words encoded in braille as compared to when listening to words, evidence that braille and audition may differentially impact retrieval among proficient braille readers (Pring, 1988). However, findings from n-back studies using the tactile modality are less clear. Bliss et al. (2004) find no differences between blind and sighted participants on an n-back task when items are encoded with braille versus using raised tactile letters. Therefore, to test for modalities' effect, the current study compares blind participants' recall of auditory and braille items to sighted individuals' recall of visual and auditory stimuli.

Considering Age and SES

An individual's age, economic, and social opportunities are important considerations when measuring executive function. Low SES is linked to poorer scores on WM measures (Ursache & Noble, 2016), and a weak but significant correlation exists between WM and income in children (Noble et al., 2015). Individuals raised in lower SES environments are at risk for poorer physical health (Crosnoe, 2006), lower vocabulary acquisition (Hart & Risley, 1995), and less access to high quality education (Murnane, 2007). The disadvantages appear early in development and remain stable through late adolescence (Hackman et al., 2014). WM abilities continue to improve until early adulthood, then decline with age (Hartshorne & Germine, 2015).

Relevant to the current study, lower educational opportunity is linked to challenges in various executive functions. Children raised in lower SES environments exhibit weaker problem-solving abilities relative to those of high SES and less interest in following instructions (Ursache & Noble, 2016). Children raised in high SES environments are exposed to more vocabulary and more complex speech very early in development relative to children raised in low SES environments (Ursache & Noble, 2016), giving children of high SES an advantage for developing language systems. Moreover, income and maternal education predict children's WM abilities such that higher income and maternal education are associated with higher WM abilities (Hackman et al., 2014).

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 & Dandona, 2001). This creates the double-disadvantage of managing a complex disability in an environment with fewer resources. Bradley and Corwyn (2002) note that those of low SES are less likely to be involved in cognitively stimulating activities, such as visiting a museum, library, or new location, enrichment opportunities that are commonly not structured for access through nonvisual means. Low SES also negatively affects individuals' nutritional intake. Nutrition impacts long-term planning and memory abilities, important strategies used to adapt to life with disabilities such as blindness (Yau, McKercher, & Packer, 2004). Despite blind individuals’ unequal access to resources, those who become blind early on may strengthen their memory abilities and partially compensate for these barriers as a resul

The current study evaluates STM and WM abilities in participants with and without impaired vision while also matching for demographic characteristics to account for SES differences. Using three established tasks, we assess the effects of blindness on STM capacity (forward digit span), WM manipulation (backward digit span), and the updating and inhibiting of items in WM (n-back). Although previous findings are mixed, we hypothesize that we may replicate previous findings of larger STM span among those who are blind compared to the sighted. Based on the degree of modularity theory of WM (Adams, Nguyen, & Cowan, 2018), we hypothesize that improved memory performance in the blind sample will extend to the more complex n-back task, which incorporates both item updating and executive function processes. Moreover, based on evidence that the sensory modality by which information is encoded impacts memory performance, we will compare STM measures on two different modalities for each group. Finally, our study hypothesizes that matching for SES will differentially impact memory performance in an SES-matched sample relative to a full sample not matched for SES. That is, when matching participants who are blind and sighted for SES-related demographic characteristics (operationalized using maternal education and family income; Sapolsky, 2004), WM performance differences will be larger than when not matching for SES. To test these hypotheses, we designed the following study in a way such that it varied modality, STM and WM load levels, and measured item duration and SES across participants.

Methods

Participants.

Ninety participants volunteered for this study (N= 58 sighted, aged 17-49; mean age = 25.7±8.16; N = 32 visually impaired, aged 18-48; mean age = 29.7±7.63). To be eligible for the study, participants who are visually impaired had to be legally blind (20/200 or less acuity in the better eye), as indicated through self-report. 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. Further details on population demographics are shown in

Table 3.1.

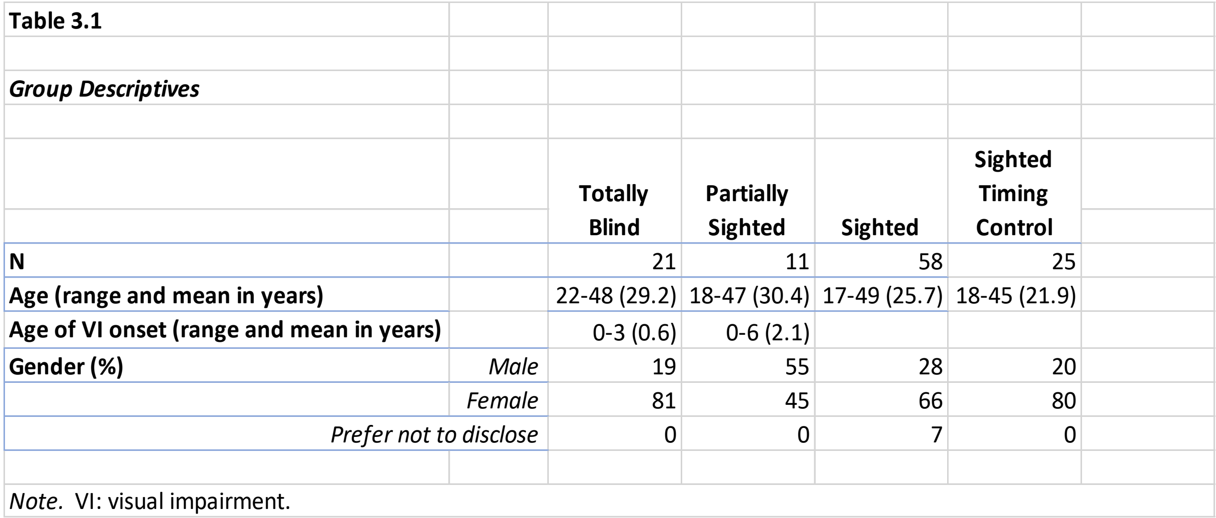

Table 3.1

Group Descriptives

		Totally Blind	**Partially Sighted**	**Sighted**	**Sighted Timing Control**
N		21	11	58	25
Age (range and mean in years)		22-48 (29.2)	18-47 (30.4)	17-49 (25.7)	18-45 (21.9)
Age of VI onset (range and mean in years)		0-3 (0.6)	0-6 (2.1)		
Gender (%)	*Male*	19	55	28	20
	Female	81	45	66	80
	Prefer not to disclose	0	0	7	0

Note. VI: visual impairment.

Table 3.1: Group Descriptive

The legally blind sample was further subdivided into two groups: Those with partial vision whose preferred reading format was large print over braille (N = 11, aged 18-47; mean age = 30.6 ± 9.24), and those whose preferred reading medium was braille (N=21 blind, aged 22-48; mean age = 29.2 ± 6.84). Of these, only 19 had complete data for both the digit span and n-back discussed in further detail below; two had incomplete n-back data. An additional group of sighted participants (N=25, aged 18-45; mean age = 21.9 ± 5.18) participated in a control experiment using the visual digit span task (described in further detail below).

Match (Van Casteren & Davis, 2007) was used to select a subset of blind (braille readers only; n = 14) and sighted (n = 14) participants from the larger group, matched on factors of age, maternal education, and income for secondary analyses holding SES equivalent across both groups. Both age and SES differed between the full samples of our two groups (cf. Table 3.2).

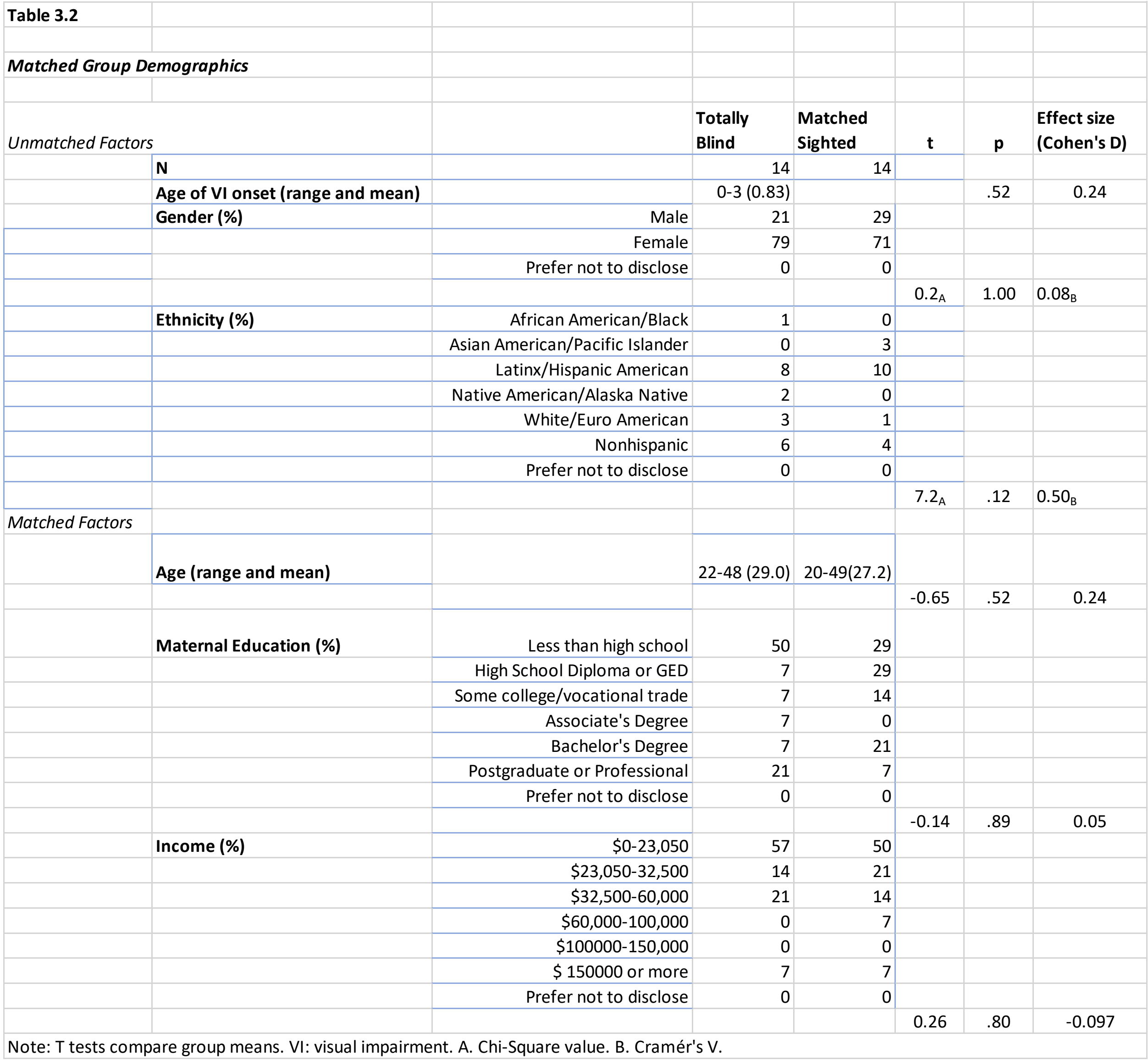

Table 3.2

Matched Group Demographics

Unmatched Factors			**Totally Blind**	**Matched Sighted**	**t**	**p**	**Effect size (Cohen's D)**
	N		14	14			
	Age of VI onset (range and mean)		0-3 (0.83)			.52	0.24
	Gender (%)	Male	21	29			
		Female	79	71			
		Prefer not to disclose	0	0			
					0.2_A	1.00	0.08_B
	Ethnicity (%)	African American/Black	1	0			
		Asian American/Pacific Islander	0	3			
		Latinx/Hispanic American	8	10			
		Native American/Alaska Native	2	0			
		White/Euro American	3	1			
		Nonhispanic	6	4			
		Prefer not to disclose	0	0			
					7.2_A	.12	0.50_B
Matched Factors							
	Age (range and mean)		22-48 (29.0)	20-49(27.2)			
					-0.65	.52	0.24
	Maternal Education (%)	Less than high school	50	29			
		High School Diploma or GED	7	29			
		Some college/vocational trade	7	14			
		Associate's Degree	7	0			
		Bachelor's Degree	7	21			
		Postgraduate or Professional	21	7			
		Prefer not to disclose	0	0			
					-0.14	.89	0.05
	Income (%)	$0-23,050	57	50			
		$23,050-32,500	14	21			
		$32,500-60,000	21	14			
		$60,000-100,000	0	7			
		$100000-150,000	0	0			
		$ 150000 or more	7	7			
		Prefer not to disclose	0	0			
					0.26	.80	-0.097

Note: T tests compare group means. VI: visual impairment. A. Chi-Square value. B. Cramér's V.

Table 3.2: Matched Group Demographics

Procedures.

All study procedures were approved by the University of California Irvine Human Subjects Institutional Review Board, and all participants consented prior to participating. Study tasks were controlled using Mac computers running MATLAB (Mathworks, Inc.) with the PsychToolbox (Brainard, 1997; Pelli, 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 while wearing a 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. Partially sighted participants who identified large print as their preferred reading medium (as compared to braille) completed the digit span task visually using enlarged print (see below). Digit span and n-back tasks were completed in counterbalanced order.

Digit Span.

Participants were presented unique lists of single digits (1-9) in pre-determined orders based on the Wechsler Memory Scale (Wechsler, 1945). After a few practice trials, participants were instructed to recall the digits either in forward or reverse order, with the two tasks completed in separate blocks. The lists ranged in length from two to twelve items, with two trials completed per list length. Lists increased in length by one digit if the participant correctly recalled all digits in order on the prior two trials. The task terminated when participants committed errors on both lists of the same length. Trials correct, our dependent variable, was computed as the total number of trials recalled correctly, summed over all list lengths. All participants completed the digit span using the same digit sequences; however, lists of items were not repeated across either the visual, auditory, or braille tasks.

Digit duration and interstimulus intervals (ISIs) were adjusted for each digit span modality to facilitate sensory encoding. Digits on the auditory span task were recorded using a female speaker, standardized to a 500 msec duration with a 1 sec ISI, and played at a comfortable volume. Digits on the visual span were displayed in black on a white screen and were visible to fully sighted participants for 500 msec with a 1 sec ISI. For individuals with partial vision who preferred reading enlarge print, the digits' font size was increased to a comfortable size for the participant. In addition, stimulus duration was extended to 750 msec (1 sec ISI) based on the finding that even after magnifying font size, those with partial vision generally read at slower speeds as compared to sighted individuals (Legge, 2016). Digit duration on the braille version was extended to 1 sec (1 sec ISI) to allow sufficient time for reading, which, even for the most advanced braille readers, is generally slower than print reading (Wetzel & Knowlton, 2000).

Auditory N-back.

Participants heard letters and were instructed to identify 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). WM load increases with the 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, Buschkuehl, Perrig, & Meier, 2010). Items were recorded using a female voice and were played back at a duration of 500 msec with an ISI of 2.5 sec.

Participants practiced the task for a list 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.

In 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.

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 500 msec duration with an ISI of 1 sec, and an extended version in which digits were presented for 1 sec with a 1 sec ISI (matching the braille span’s duration and timing). Lists and visual digit span versions were counterbalanced across participants.

Demographic Questionnaire

All participants completed a demographic questionnaire that collected information about participants' gender, age, SES (income, education level of participants and both of their parents), ethnicity, and whether they were diagnosed with neurological disorders or cognitive or psychiatric disabilities (Appendix Table 1). In addition, participants who are blind answered questions about the severity and onset of their blindness, rated their braille proficiency level, braille reading frequency, and reported their preferred reading medium. Eighteen participants who were blind answered additional questions about their blindness, providing details on whether or not they could see shapes, color, or motion, as well as their current and maximum visual acuity, and whether or not they perceived light. Participants also answered questions about their blindness onset, including the ages (in years) at which they stopped having functional vision and reading print, as well as when they became totally blind for those whose vision loss was progressive.

Results

Digit Span

A one-way repeated measures ANOVA with directionality (forward vs. backward) as the within-subject factor and group (blind vs. sighted) as the between-subject factor using the auditory span as outcome revealed a main effect of group on auditory span accuracy ($F(1, 77) = 39.56$, $p < .001$, $\eta_p^2 = 0.34$) such that blind participants recalled significantly more items than sighted participants (cf. Figure 3.1). We found neither a main effect of directionality (F(1, 155) = 1.35, p = .25, $\eta_p^2 = 0.02$), nor an interaction between directionality and group (F(1, 155) = 0.97, p = .33, $\eta_p^2 = 0.01$).

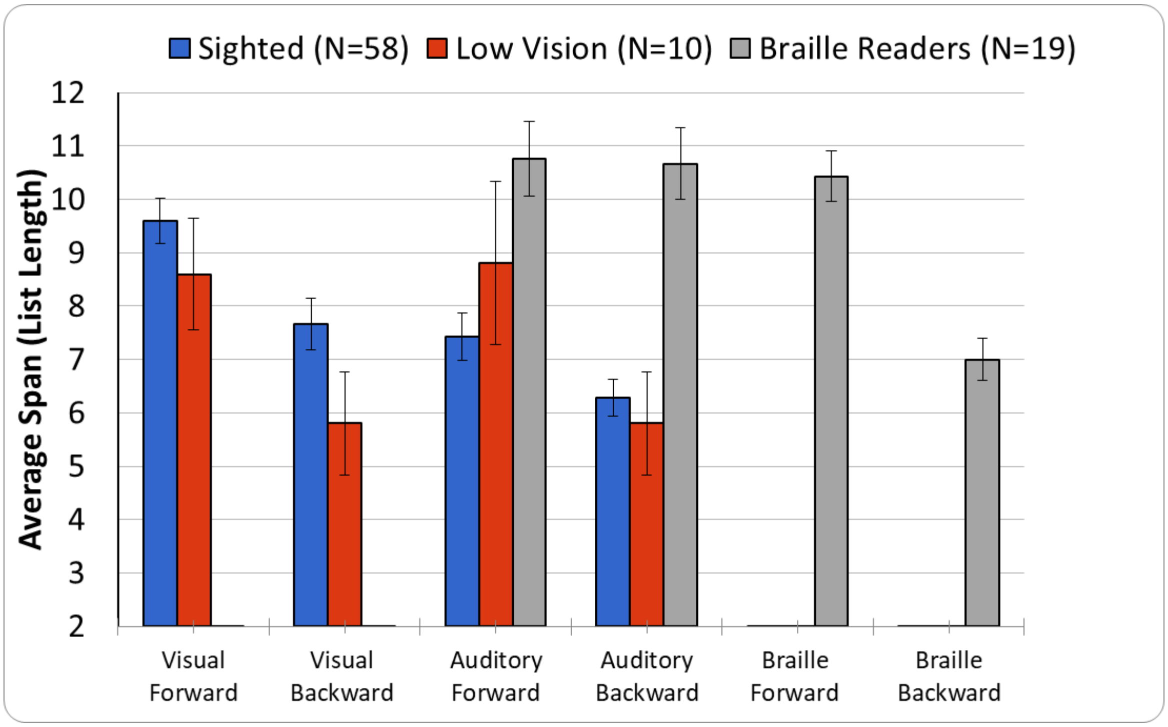

Figure 3.1: Average visual, auditory, and braille digit span trials correct across all sighted participants and among those who are blind

We also tested whether the modality in which the item was encoded (auditory, visual, or tactile) impacted memory span performance. Trials correct 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 one-way repeated measures ANOVA revealed a main effect of modality (F(1, 114) = 30.57, p < .001, $\eta_p^2 = 0.35$). Sighted individuals recalled more items after encoding the list visually rather than when heard. The load x modality interaction in sighted participants was not significant ($F(1, 57) = 1.49$, $p = .227$, $\eta_p^2 = 0.03$).

In contrast, blind participants recalled more items when heard versus read in braille ($F(1, 40) = 19.39$, $p < .001$, $\eta_p^2 = 0.49$). We also found a significant directionality by modality interaction in the blind participants when reading braille ($F(1, 40) = 6.29$, $p = .02$, $\eta_p^2 = 0.24$). A post-hoc test indicated that blind participants recalled more digits in forward as compared to reverse order when reading in braille, though not when listening to lists ($t(20) = 8.96$, $p < .001$, $\eta_p^2 = 1.41$).

To evaluate cognitive load's (forward vs backward recall) impact while controlling for encoding modalities across groups, we conducted a subsequent analysis using standardized z-scores of the difference in accuracy across modalities. A two-way repeated measures ANOVA comparing trials correct revealed neither a main effect of directionality ($F(1, 155) = 0.001$, $p = .98$, $\eta_p^2 = 0.000$) nor a main effect of group ($F(1, 77) = 0.02$, $p = .901$, $\eta_p^2 = 0.000$). We also found no evidence for a recall by group interaction ($F(1, 155) = 0.001$, $p = .98$, $\eta_p^2 = 0.000$).

N-back

A two-way ANOVA with n-back level (one through four-back) as the within-subject factor and group (blind and sighted) as the between-subject factor revealed a main effect of n-back level on accuracy ($F(3, 295) = 128.75$, $p < .001$, $\eta_p^2 = 0.64$), such that accuracy decreased as a function of n-back level, which reflects increased WM load. We found no evidence, however, to support the hypothesis that blind participants outperform sighted participants. That is, we found neither a main effect of group (F(1, 73) = 0.37, p = .55, η_p^2 = 0.005) nor an n-back level by group interaction (F(3, 295) = 0.31, p = .82, η_p^2 = 0.004; cf. Figure 3.2).

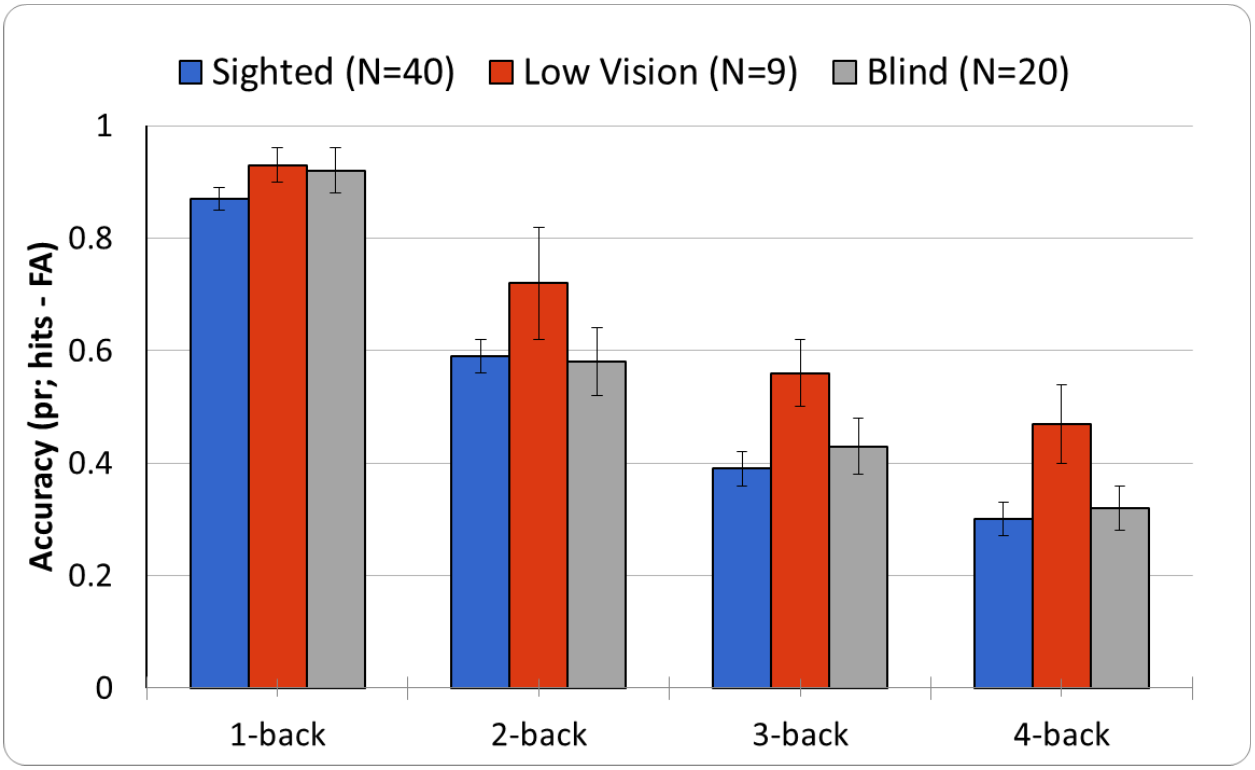

Figure 3.2: Average N-back PR scores across all sighted participants and among those who are blind

Using reaction times (RTs) as an outcome measure, we found a main effect of n-back level (F(3, 295) = 26.72, p < .001, η_p^2 = 0.27), again indicating that increasing load was associated with slower RTs. In addition, we found a main effect of group (F(1, 73) = 4.29, p = .04, η_p^2 = 0.06; cf. Table 3.3). Specifically, sighted participants responded faster than blind participants. The interaction between group and n-back level was not significant (F(3, 295) = 1.302, p = .28, η_p^2 = 0.02).

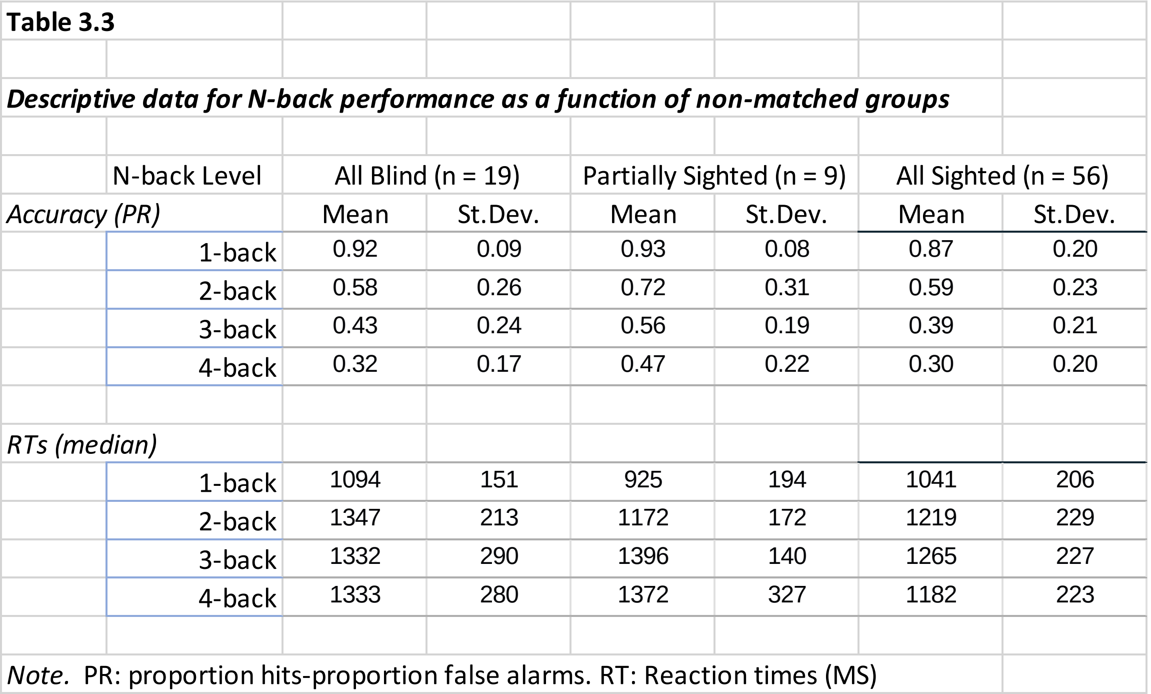

Table 3.3

Descriptive data for N-back performance as a function of non-matched groups

	N-back Level	All Blind (n = 19)		Partially Sighted (n = 9)		All Sighted (n = 56)	
Accuracy (PR)		Mean	St.Dev.	Mean	St.Dev.	Mean	St.Dev.
	1-back	0.92	0.09	0.93	0.08	0.87	0.20
	2-back	0.58	0.26	0.72	0.31	0.59	0.23
	3-back	0.43	0.24	0.56	0.19	0.39	0.21
	4-back	0.32	0.17	0.47	0.22	0.30	0.20
RTs (median)							
	1-back	1094	151	925	194	1041	206
	2-back	1347	213	1172	172	1219	229
	3-back	1332	290	1396	140	1265	227
	4-back	1333	280	1372	327	1182	223

Note. PR: proportion hits-proportion false alarms. RT: Reaction times (MS)

Table 3.3: Descriptive data for N-back performance as a function of non-matched groups

Groups Matched on Age and SES

Digit Span

In the matched sample, a two-way repeated measures ANOVA on the auditory digit span accuracy scores as outcome revealed a main effect of group ($F(1, 26) = 9.695$, $p = .004$, $\eta_p^2 = 0.27$), which is consistent with the full sample's results. We found neither an effect of directionality (forward vs. backward; $F(1, 53) = 0.296$, $p = .59$, $\eta_p^2 = 0.01$) nor an interaction between group and directionality ($F(1, 53) = 0.07$, $p = .801$, $\eta_p^2 = 0.002$; cf. Figure 3.3).

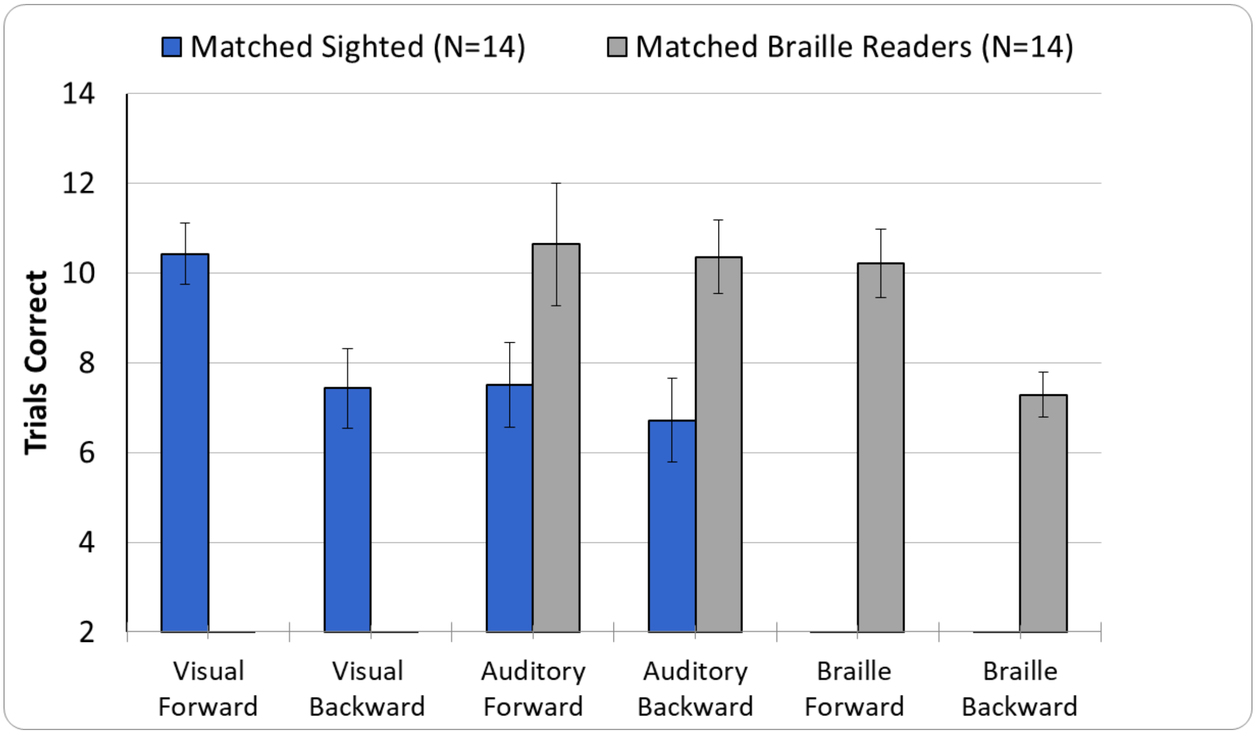

Figure 3.3: Average visual, auditory, and braille digit span trials correct across matched sighted and blind participants

N-back

In contrast to the full sample, when matched for age and SES, we found a significant main effect of group on n-back accuracy (F(1, 26) = 4.66, p = .04, $\eta_p^2 = 0.15$), namely, blind participants significantly outperformed sighted participants. No interaction between group and n-back level was found (F(3, 107) = 1.05, p = .38, $\eta_p^2 = 0.04$; cf. Figure 3.4).

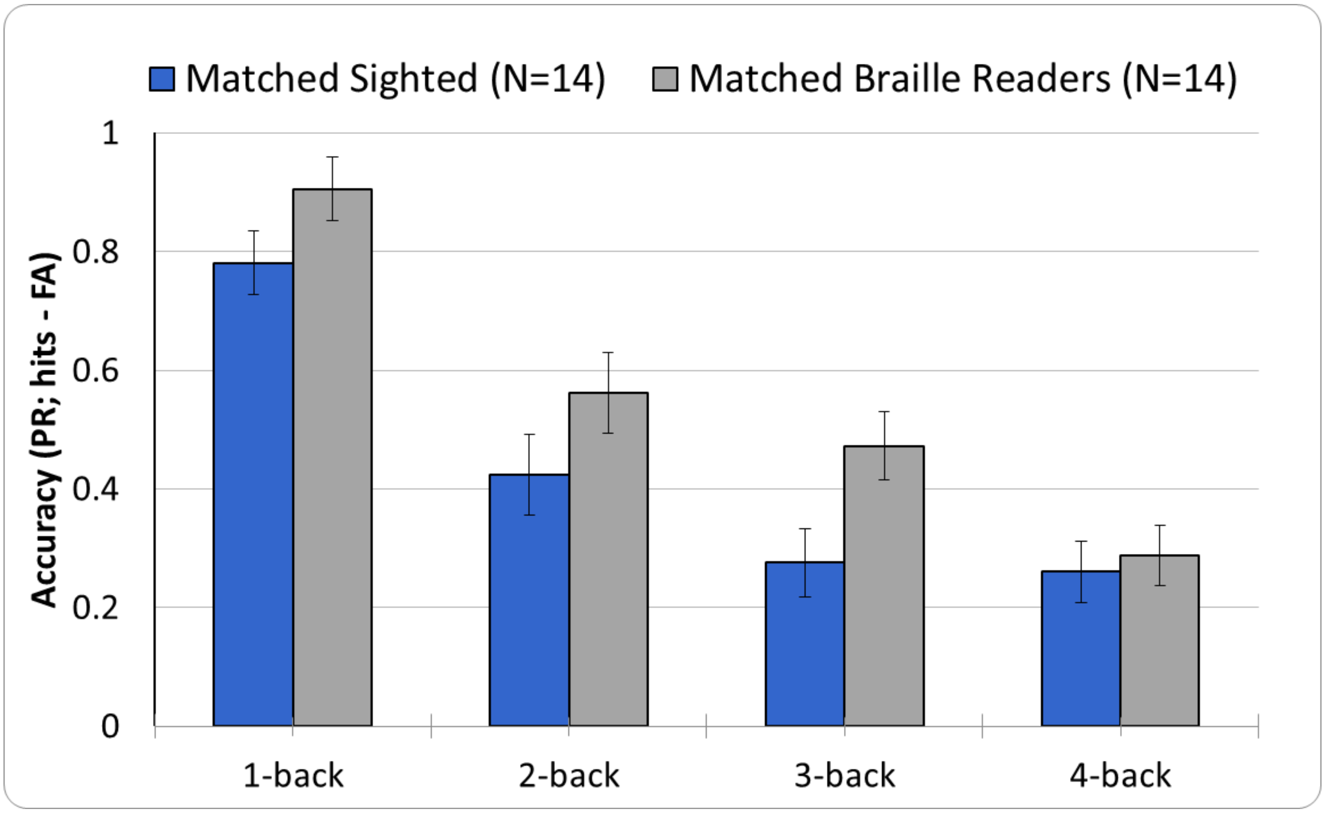

Figure 3.4: Average N-back PR scores across matched sighted and blind participants

For RTs, again contrasting what we observed in the full sample, we found no main effect of group ($F(1, 26) = 1.65$, $p = .21$, $\eta_p^2 = 0.06$), and the group by n-back level interaction was not significant either ($F(3, 107) = 0.87$, $p = .46$, $\eta_p^2 = 0.03$).

Considering Lures (n-back)

One measure of the n-back task's attention control demands is the accuracy with which lures are correctly classified as non-targets. Lures measure attentional control in managing the cognitive interference imposed between temporally adjacent items (Kane, Conway, Miura, &

Colflesh, 2007). We found no main effect of n-back level on sensitivity to lures in our full sample ($F(2, 221) = 0.602$, $p = .55$, $\eta_p^2 = 0.01$), no main effect of group on lure accuracy ($F(1, 73) = 2.58$, $p = .11$, $\eta_p^2 = 0.03$), nor an n-back level by group interaction ($F(2, 221) = 1.06$, $p = .35$, $\eta_p^2 = 0.01$). Both groups were equally effective in retaining the relevant item and position information required to complete the n-back task. The results were similar within the demographically matched sample (all p's > .05).

Digit Span in Participants with Partial Vision

In this study, our sample population included participants with partial vision, which includes individuals with a visual acuity of 20/200 or less in the better eye and the ability to read printed text when enlarged. The age of onset of visual impairment in our sample with partial vision did not differ statistically from the blind population ($t(30) = 0.49$, $p = .630$, $\eta_p^2 = .01$). However, we note that individuals with partial vision may use their vision to complete tasks that blind individuals would achieve auditorily or via braille, hence relying on memory systems less than participants who are blind.

An exploratory two-way repeated measures ANOVA evaluated the factors of directionality (forward vs backward recall order) on the auditory digit span task for three groups of sighted, blind braille readers, and partially sighted large print readers. We found a main effect of directionality among these participants ($F(1, 176) = 6.94$, $p < .001$, $\eta_p^2 = 0.07$) such that recalling the items backwards resulted in significantly lower accuracy than recalling the items in forward order.

The analysis also revealed a main effect of group ($F(2, 87) = 19.43$, $p < .001$, $\eta_p^2 = 0.31$). Post-hoc tests revealed significantly higher digit spans among those who are blind compared to the sighted ($p < .001$) and partially sighted ($p = .001$). No differences were found between those with full vision and those with partial vision ($p = 1.00$). Thus, participants with partial vision are disadvantaged in recalling heard items relative to participants who are blind. No interaction between group and directionality was found ($F(2, 176) = 1.83$, $p = .17$, $\eta_p^2 = 0.04$).

A test of modality (visual vs auditory) in participants with partial vision on digit span trials correct revealed no main effect of the modality by which the items were encoded ($F(1, 20) = 3.88$, $p = .08$, $\eta_p^2 = 0.301$).

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 encoding as compared to the rapid, visually presented items (500 msec, with a 1 sec ISI). The extended stimulus duration may have driven the improved recall in individuals who are blind, perhaps as a result of additional time for verbal rehearsal. Therefore, a new 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, blocked and 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 ($F(1, 48) = 26.88$, $p < .001$, $\eta_p^2 = 0.53$). However, the sighted participants performed better on the *shorter* duration trials as compared to the longer duration trials. Therefore, the longer exposure duration does not facilitate recall and instead appears to promote item decay due to the longer presentation times (Ricker, Spiegel, & Cowan, 2014). Thus, timing does not seem to explain the group differences observed between individuals who are sighted and blind.

Discussion

This study evaluates how visual deprivation might impact STM and WM abilities. Additionally, it considers sensory modalities for information encoding and individuals' SES. Consistent with previous studies (Bottini et al., 2016; Withagen et al., 2013), we find that those who are blind have a clear advantage over sighted individuals on digit span task performance, while we only see this advantage in the n-back task once we controlled for age and SES.

Digit Span

Our finding that adults who are blind outperform the sighted on both auditory forward and backward digit span tasks replicates previous studies (Occelli et al., 2017; Raz et al., 2007; Rokem & Ahissar, 2009). One hypothesis for improved STM among the blind sample is the additional use of memory strategies to complete daily tasks such as navigating and locating objects, an extensive form of training in ecological settings. Some of these memory strategies include chaining (i.e., associating adjacent items to one another based on their positions in space or on timing intervals between items). Another strategy may be ordinal position recall, which is improved in individuals who are blind as compared to the sighted (Raz et al., 2007). Sighted individuals trained to use chaining when recalling word lists in STM have improved both their sTM and WM capacity relative to non-trained controls (McNamara & Scott, 2001), and the same study finds that those with higher memory capacity benefit more from memory strategies as compared to those with lower memory capacity. Perhaps blind individuals may have a higher verbal memory capacity compared to the sighted, which in turn may facilitate their use of chaining and ordinal positions when recalling items in STM and increase their recall on simpler WM tasks.

An additional analysis of sighted and blind participants matched for age, income, and maternal education returned results similar, albeit with slightly lower effect size, to that obtained for our unmatched sample. Participants who are blind outperformed the sighted in both the matched and unmatched samples despite the unmatched sample drawing from a more socioeconomically disadvantaged population. We take this as evidence that blind individuals' STM capacity is robust to the SES factors that otherwise adversely impact executive function. However, we still recommend participant SES be considered due to its association with WM, which may possibly unmask differences and explain why evidence of improved WM in blind over sighted is more mixed.

We further find that blind individuals' STM advantage is transferrable across encoding modalities. Participants who are blind showed a clear benefit over the sighted when encoding items auditorily as compared to a very slight advantage when reading the items in braille. The reason for this is not entirely clear. We noted in a post-hoc analysis that blind participants recalled significantly fewer digits in reverse than in forward order when reading them in braille, evidence for a load effect that was not apparent in the auditory span task. This difference suggests that perhaps sensory experience in the auditory modality may facilitate blind individuals developing greater auditory WM abilities relative to tactile WM performance (Cohen et al., 2010). Blind individuals may only exhibit a memory advantage over the sighted for auditory, verbal information with comparable performance between blind and sighted participants for verbal stimuli presented visually and in braille. Our finding similar performance for blind individuals' braille WM relative to sighted individuals' visual WM suggests that both groups may have comparable WM in these modalities. When reading letters silently, blind individuals have been found to recall letters in braille equally well as compared to sighted individuals performing the same task using printed letters (Cohen et al., 2010). However, why blind individuals appear to have greater auditory as compared to tactile WM remains unclear. Because this is the first study to compare blind and sighted participants cross-modally on a digit span task to our knowledge, these explanations warrant more investigating to add to the scarce literature.

Additionally, our participants may have benefited less from re-exploring braille that is typical in ecological settings because the digits were only presented for a fixed, time-limited duration. The inability to explore may explain, in part, the contrast between our results and those of prior reports finding that blind children recalled more words in braille than when heard (Pring, 1988). Children in that study read words in braille on paper; the experimenter paced the task based on the child's reading speed but only until the maximum reading duration was reached. Moreover, in that study the children recalled word pairs in a recognition memory task, rather than sequential lists of items in a span task. Thus, these task differences likely reflect different cognitive mechanisms supporting unique mnemonic strategies, so the difference in stimuli -- words vs. numbers -- may contribute.

With respect to sighted participants, we replicated a past study finding higher performance when encoding numbers visually as compared to auditorily (Frick, 1984). The current study is the first to compare digit span performance across modalities in blind and sighted individuals. Interestingly, we found no effect of reversing item order in either population. Thus the increased load of backwards item recall may not have been demanding enough.

Besides modality-dependent differences in recall accuracy among sighted and blind participants, we also found that load uniquely affected sighted participants and not those who are blind. Recalling items in reverse order was more taxing for sighted participants using both visual and auditory input, whereas participants who are blind could recall the same number of digits in forward or reverse order when listening to the digits. Braille may pose a higher load in participants who are blind since their performance was only impaired when recalling items in reverse order using braille. They may manipulate and recall items more readily when presented auditorily due to using auditory information more frequently and to representing items verbally, whereas evidence suggests WM for braille is similar to sighted individuals' visual WM and that braille is more spatial in nature. Matching for SES characteristics may also explain the mixed evidence regarding between-group differences.

N-back

N-back tasks rely more extensively on executive functions relative to the digit span (Kane et al., 2007). Previous work utilizing the n-back in blind and sighted participants find no differences between both populations regardless of the encoding modality or stimuli in use (Bliss et al., 2004; Park et al., 2011; Pigeon & Marin-Lamellet, 2017).

Importantly, however, those studies failed to carefully assess and match groups for SES, which is known to impact WM abilities. Whereas only age (Bliss et al., 2004; Park et al., 2011;

Pigeon & Marin-Lamellet, 2017) and participants' education (Park et al., 2011; Pigeon & Marin-Lamellet, 2017) were considered in prior work, our study carefully matched for age, education, and SES. We observed that group differences on the auditory n-back task emerged only when those factors were controlled. Our work highlights the importance of carefully considering nontraditional factors that may otherwise mask differences, and in particular improvements, in executive function that may emerge from sensory deprivation.

Accuracy differences may only emerge in matched as opposed to in non-matched samples due to interference resolution as measured by lures. Our hypothesis of lower accuracy with increased n-back level among both participants with and without vision was supported in all but the most difficult n-back levels. Unlike prior work which tested participants on one through 3-back tasks (Pigeon & Marin-Lamellet, 2015, 2017), we tested participants up to a 4-back task and still found accuracy differences across matched groups. These results lead us to conclude that number of n-back levels tested does not explain the differences between matched groups. Though we find that sighted participants respond more quickly than participants who are blind when measuring n-back reaction times in our entire sample, this timing difference disappears in our matched sample, suggesting timing may not explain matched group differences either. Consequences of blindness, and not task design, may thus explain these differences only after controlling for SES.

Several possible explanations exist as to why group differences may only have been found on the n-back after matching for SES characteristics. First, the difficulty of an n-back task as measured by load levels may influence whether or not one group outperforms the other. Load affects how taxing a task is for participants, with higher loads being more demanding regardless of task content. Previous verbal and nonverbal n-back studies find that increasing load leads to poorer performance in blind and sighted participants equally regardless of content or modality being used (Gudi-Mindermann et al., 2018; Park et al., 2011), consistent with what was observed in this study. Task complexity may mitigate the benefits of memory strategies, such as serial recall (Raz et al., 2007), with outcomes more reflective of other cognitive demands, including the need to update memory representations.

Age of blindness onset is important to examine when considering the potential for cognitive compensation and cortical reorganization due to sensory deprivation (Bavelier & Neville, 2002). Early onset blindness provides dual opportunity for memory training, through cortical plasticity during a critical developmental window and as a result of extensively practicing memory strategies daily to promote functional independence. The majority of participants in this study became visually impaired at or before age six (cf. Appendix table 1), which is consistent with reports of improved memory span in children who are early blind as compared to individuals with late blindness onset (Dormal et al., 2016; Hull & Mason, 1995; Smits & Mommers, 1976; Tillman & Bashaw, 1968; Withagen et al., 2013). Whether a late blind population would demonstrate the same STM and WM superiority we have documented here remains unclear.

Participants with Partial Vision

Participants with partial vision exhibited a different pattern of results compared to blind and sighted participants, possibly due to strategies used or plasticity. Participants with partial vision remembered fewer digits on the digit span compared to those who are blind and sighted regardless of modality, thus replicating previous null differences between partially sighted and sighted participants on a digit span (Bathelt et al., 2018). In spite of using visual strategies to complete tasks with their remaining vision, i.e., magnification equipment and contrast (Smith, Ludwig, Andersen, & Copolillo, 2009), those with partial vision may recall less than sighted participants on the digit span task due to developing visual strategies less extensively. With respect to participants who are blind and those with partial vision, the difference in digit span accuracy between them suggests the blind use memory strategies most effectively due to their need to remember information such as spatial locations, linguistic information, etc. unlike participants with full or partial vision who may use their sight to access such information rather than recalling it from memory. Therefore, participants with partial vision may develop their WM abilities less than those who are blind. Another plausible explanation is that those with partial vision may have weaker neural connections for visual input (Cohen, Scherzer, Viau, Voss, & Lepore, 2011), leading to lower performance on the visual digit span.

A slight group effect was also found for n-back accuracy when comparing sighted participants to those who are blind and to those who have partial vision. Those with partial vision only significantly outperform sighted participants accuracy-wise, suggesting that the strategies that those with partial vision use are effective to a certain extent for the n-back task relative to those of sighted participants. To our knowledge, this study is the first to assess WM in participants with partial vision using an n-back task, and our sample of participants with partial vision is small. Therefore, these explanations warrant more investigating to add to the scarce literature.

Conclusions and Future Directions

Overall, this study finds that participants who are blind outperform sighted participants on STM and WM tasks. This superiority is found in an even more complex WM task, apparent when care is taken to match the groups for moderating factors (age and SES demographic characteristics). Therefore, we conclude the blind have an advantage over the sighted in both STM capacity and in their ability to cognitively manipulate information.

While we do find that blindness influences memory performance, much remains to be understood of memory abilities, namely how visual deprivation contributes to developing this superiority. More research is also needed to understand how information modality may interact with encoding, given the benefits we observed for auditory and braille encoding. Based on the importance of objective and subjective SES measures on WM scores, future research should address how susceptible these functions are to stressors and when the benefits emerge developmentally. Importantly, we conclude that blindness contributes to unique cognitive strengths, such as memory benefits as compared to sighted individuals, illustrating neuroplasticity.

Conclusion

STM and WM are particularly important for individuals who are blind in daily life. Researchers propose that extensive use of memory strategies in blindness may result in improved STM capacity relative to sighted individuals. The extent to which this applies to nonverbal recall and more complex memory function is unclear. Moreover, evidence is mixed regarding whether or not between-group differences are found. Some report between-group differences on STM span tasks (Hull & Mason, 1995; Raz et al., 2007; Rokem & Ahissar, 2009), while others do not (Castronovo & Delvenne, 2013; Ekstrom, 2018; Wyver & Markham, 1998), potentially due to samples' inclusion criteria.

WM findings among blind and sighted participants are also mixed for reasons that are less clear. Some studies find blind participants outperform the sighted on span tasks and on tasks involving interference (Cornell Kärnekull et al., 2016; Dormal et al., 2016; Occelli et al., 2017; Rindermann et al., 2020; Röder et al., 2001; Withagen et al., 2013). Again, other studies find no advantage for blind over sighted participants on span and n-back tasks (Burton et al., 2010; Castronovo & Delvenne, 2013; Park et al., 2011; Swanson & Luxenberg, 2009).

To better understand if STM and WM variations may exist in blind relative to sighted individuals, this dissertation explored potential factors that may contribute to the possible between-group differences. Individuals who are blind, partially sighted, and fully sighted were tested on several STM, WM, and recognition memory tasks to understand if characteristics including verbal and nonverbal stimuli, encoding modality, and SES contribute to STM and WM between-group differences. We found that blind individuals outperformed the sighted on all verbal STM tasks and some WM tasks. Blind and sighted participants performed equally well on nonverbal recognition memory tasks, suggesting blind individuals may have a verbal memory advantage over sighted individuals. We also found that modality is associated with memory performance and that differences on more complex WM tasks only emerge after participants are matched for SES. Our finding performance differences on all STM tasks and only on some WM tasks suggest that the processes involved in STM and WM may vary. Were they identical, performance differences would be more consistent between-groups and across tasks. Whereas retrieving information from STM involves merely recalling items in free or serial order, WM may involve task-dependent processes, i.e., interference on the verbal complex span task or updating on the n-back task. Therefore, our finding differences on the verbal complex span task with interference and on the n-back only after matching for SES across groups suggest that the magnitude of WM comparisons between blind and sighted individuals may depend on which mechanisms the task involves. The extent to which groups are matched for demographic characteristics associated with WM in combination with task complexity may be one reason why findings are mixed. What is clearer from these results is that STM and WM are differentiable. The reasons for and the extent to which between-group differences emerge on WM have yet to be fully understood.

Systematic Review

The first chapter presents a systematic review of the STM and WM literature among those who are blind and sighted to assess if between-group differences in memory ability exist and potential factors that may explain these differences based on existing knowledge. In spite of the limited literature comparing memory across these populations, the literature varies with respect to task design, participant inclusion and exclusion criteria, and results. After systematically comparing results across articles according to effect sizes (Cohen's d) and vote counting, we conclude that characteristics such as age of blindness onset, verbal and nonverbal material, and demographic characteristics shown to influence WM including SES factors, chronological age, and age of blindness onset appear to influence whether or not between-group differences in STM and WM are found. We recommend matching future participants for such characteristics and documenting the inclusion criteria used to possibly identify findings that may otherwise be masked.

Superior Verbal over Nonverbal Memory in Congenital Blindness

The second study sought to understand if those who are blind have higher working and recognition memory relative to the sighted for stimuli that are verbal, nonverbalizable, or both. Verbal information is critical to blind individuals informing themselves about their environment. This series of three experiments tested age and education-matched blind and sighted participants' recall abilities on verbal WM tasks with and without verbal interference, as well as their nonverbal and verbal recognition memory using meaningless nonverbal stimuli and letters. Blind individuals outperformed the sighted on all verbal memory tasks including one with verbal interference, thus replicating and extending past findings due to a more demanding interfering task (Dormal et al., 2016; Röder & Rösler, 2003; Röder et al., 2001; Withagen et al., 2013). While blind participants also outperformed sighted participants on the nonverbal recognition memory task, only one load contributed to this effect in contrast to previous work finding better memory for verbalizable sounds in blind as compared to sighted individuals (Cornell Kärnekull et al., 2016; Röder & Rösler, 2003). This study extends previous work by questioning verbal stimuli's role in the memory differences observed between groups rather than questioning if only between-group memory differences exist. Both this study and the review find higher between-group differences for verbal over nonverbal memory, lending more support to blindness related memory advantages being specific to verbal information. We recommend future work test not only if memory differences exist between blind and sighted individuals but also provide more behavioral or imaging evidence as to why differences may be greatest for verbal memory.

Influence of Modality and SES on WM

Because encoding modality has been shown to uniquely influence WM, The third study sought to understand if modality contributes to the verbal STM and WM improvement found in some studies of blind over sighted participants (Frick, 1984; Pring, 1988). Since SES has also been shown to influence WM abilities primarily in studies of sighted individuals, this study also examined the link between matching blind and sighted participants for socioeconomic factors and the magnitude of between-group WM differences (Hackman et al., 2014; Noble et al., 2015).

To clarify the role of modality on STM and WM abilities, the final study tested blind, partially sighted, and sighted adults' STM and WM abilities using digit span tasks while also manipulating the modality used to encode items—visual, auditory, and haptic using braille. WM was further tested using a more complex auditory n-back task. Our full sample differed on factors of age, education, and income, so a subset of blind and sighted participants matched for age, maternal education, and income was created to compare results across samples when socioeconomic factors were and were not controlled for.

We replicate prior findings in that blind participants outperformed those with full and partial vision in the full sample and in the matched sample. However, blind participants recalled more items when heard as compared to when read in braille, suggesting that at least in this controlled context, braille may be more taxing to blind participants, whereas sighted participants recalled more items visually as compared to when heard. In the full sample of participants, a trending group difference was found on the n-back task where partially sighted participants scored higher than sighted participants, though we found no evidence for performance differences on remaining group comparisons. Unlike the full sample which found nonsignificant differences between blind and sighted participants on the n-back task, we found blind participants significantly outperformed the sighted in the matched samples even in this more demanding task. Again, these results suggest that taking demographic factors linked to memory in to account is crucial to manifest improvements that may not have been identified otherwise. Doing so may begin to clarify the mixed findings in the literature. Testing both blind and sighted participants cross-modally can improve our understanding of the extent to which each modality may distinctly influence each group's memory abilities depending on experience.

Memory processes such as storage and interference may also be malleable to blindness-related experience. Our data suggest that perhaps storage for auditory information may be higher in blind over sighted participants possibly due to blind individuals constantly relying on auditory STM for gaining information and due to auditory information's greater transience relative to the visual and tactile modalities. In contrast, sighted individuals' storage capacity when encoding auditory information may be less developed relative to when encoding visual information as their higher performance on visual over auditory digit spans suggest (Frick, 1984). However, blind individuals may recall more using auditory relative to tactile information, suggesting that modality-related experiences may contribute to modality-specific differences in performance. Moreover, sighted individuals appear to be more susceptible to decay unlike blind individuals. Our finding that sighted participants perform worse on digit spans with longer as opposed to shorter ISIs suggests sighted individuals may maintain information in STM and WM less effectively than blind participants. Blind individuals outperforming the sighted on both components of the complex span also suggests that blind individuals may be less susceptible to interference as compared to sighted participants. On the other hand, blindness may not contribute to updating abilities as the null results from the n-back lure analysis suggest.

Overall, our data identified inconsistencies in prior literature and provided insights into the influences of verbal and nonverbal stimuli, modality, and SES on WM abilities, thus replicating and extending prior findings. We aimed to clarify how these characteristics impacted individuals' use of WM as a cognitive mechanism, particularly when adapting to blindness. Our evidence suggests that to better understand reasons for the possible verbal memory ability improvements in blind over sighted participants reported in some studies thus far, authors need to consider factors other than visual deprivation. For example, task characteristics such as encoding modality and stimulus types appear to influence memory differences, with more pronounced differences on verbal as compared to nonverbal memory. Equally important, matching participants on SES measures is relevant. Not only are these associated with WM, but individuals with disabilities are more likely to come from low SES backgrounds, possibly due to health inequality (Dandona & Dandona, 2001). Therefore, controlling for socioeconomic factors increases the likelihood that differences found are more attributable to memory and not to outside factors like differing cognitive abilities. We conclude that improving our understanding of cognitive strengths stemming from sensory deprivation has much to contribute to neuroscience and to these populations in applied settings.

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Appendix Table 1

Participant Demographics among Visually Impaired

	Participant	Visual Diagnosis	Visual Impairment Severity	VI Onset (years)	Preferred Reading Medium	Braille Reading Frequency	Braille Reading Proficiency in English	Age Learned Braille (years)	Light Perception
Totally Blind	sub-84	Retinopathy of Prematurity	Totally Blind	Birth	Braille	Very often/daily	Excellent	2	no
	sub-86	Retinal Dysplasia	Totally Blind	Birth	Braille	Very often/daily	Excellent	26	minimal
	sub-88	unknown	Totally Blind	Birth	Braille	Very often/daily	Perfect	4	unknown
	sub-91	Microphthalmia due to Pseudoglioma Syndrome	Totally Blind	Birth	Braille	Very often/daily	Excellent	2	no
	sub-92	unknown	Totally Blind	Before age 6	Braille	Very often/daily	Excellent	6	unknown
	sub-93	unknown	Totally Blind	Between ages 6-12	Braille	4 times/week or less	Slightly less than adequate	9	unknown
	sub-94	Optic Nerve Hypoplasia	Totally Blind	Birth	Braille	4 times/week or less	Perfect	3	yes
	sub-95	Retinoblastoma; Bilateral Enucleation	Totally Blind	1 year and 1 month	Braille	Very often/daily	Very good	6	no
	sub-96	Retinoblastoma	Totally Blind	11 months	Braille	Very often/daily	Excellent	3	N/A
	sub-97	Glaucoma	Totally Blind	3 years	Braille	Rarely once or twice a year	Slightly less than adequate	10	minimal
	sub-107	Retinopathy of Prematurity	Totally Blind	Birth	Braille	Very often/daily	Perfect	4	yes
	sub-109	Glaucoma	Totally Blind	3 years	Braille	Very often/daily	Perfect	4	yes
	sub-112	Retinopathy of Prematurity	Totally Blind	Birth	Braille	Somewhat often once or twice a month	Perfect	6	no
	sub-114	Retinal Detachment	Totally Blind	2 years	Braille	4 times/week or less	Perfect	6	no
	sub116	unknown	Totally Blind	Birth	Braille	Very often/daily	Perfect	5	no
	sub-119	Leber's congenital amaurosis	Totally Blind	Birth	Braille	Very often/daily	Perfect	4	yes
	sub-122	Leber's congenital amaurosis	Totally Blind	Birth	Braille	Very often/daily	Perfect	3	yes
	sub-123	Glaucoma; Cataracts	Totally Blind	Birth	Braille	Very often/daily	Excellent	5	no
	sub-124	Cataracts; Glaucoma	Totally Blind	6 months	Human Reader/Recording	4 times/week or less	Good	30	yes
Partially Sighted	sub-89	Morning Glory; Retinal Detachment	Partially Sighted/Low Vision	Birth	Large print	4 times/week or less	Good	16	N/A
	sub-90	Retinopathy of Prematurity	Partially Sighted/Low Vision	Birth	Large print	4 times/week or less	Slightly more than adequate	8	N/A
	sub-98	Cataracts; Nistagmus; Aphakia (lense removal)	Partially Sighted/Low Vision	Birth	Human Reader/Recording	Rarely once or twice a year	Fair	5	N/A
	sub-100	Glaucoma; Stickler Syndrome	Partially Sighted/Low Vision	Birth	Large print	n/a	n/a	n/a	N/A
	sub-102	unknown	Partially Sighted/Low Vision	Before age 6	Large print	n/a	n/a	n/a	unknown
	sub-103	unknown	Partially Sighted/Low Vision	Birth	Screen Reader	Somewhat often once or twice a month	Slightly more than adequate	14	unknown
	sub-104	unknown	Partially Sighted/Low Vision	After age 12	Large print	Very often/daily	Slightly more than adequate	24	unknown
	sub-108	Glaucoma	Partially Sighted/Low Vision	Birth	Screen Reader	Very often/daily	Slightly more than adequate	17	N/A
	sub-110	Cone-rod dystrophy	Partially Sighted/Low Vision	5 years	Screen Reader	n/a	n/a	n/a	N/A
	sub-113	unknown	Partially Sighted/Low Vision	6 years	Large print	n/a	n/a	n/a	N/A
	sub-118	Leber's congenital amaurosis	Partially Sighted/Low Vision	Birth	Human Reader/Recording	Rarely once or twice a year	Slightly more than adequate	10	unknown
	sub-120	Glaucoma	Partially Sighted/Low Vision	Birth	Screen Reader	Rarely once or twice a year	Adequate	7	unknown
	sub-130	Retinitis Pigmentosa	Partially Sighted/Low Vision	6 years	Screen Reader	4 times/week or less	Slightly less than adequate	30	N/A

Note. N/A refers to not applicable data. Unknown refers to incomplete data.

1.1 Appendix Table: Participant Demographics among Visually Impaired