The Nature of Working Memory for Braille
Henri Cohen1,2,3, Patrice Voss4, Franco Lepore4, Peter Scherzer2

Abstract

Blind individuals have been shown on multiple occasions to compensate for their loss of sight by developing exceptional abilities in their remaining senses. While most research has been focused on perceptual abilities per se in the auditory and tactile modalities, recent work has also investigated higher-order processes involving memory and language functions. Here we examined tactile working memory for Braille in two groups of visually challenged individuals (completely blind subjects, CBS; blind with residual vision, BRV). In a first experimental procedure both groups were given a Braille tactile memory span task with and without articulatory suppression, while the BRV and a sighted group performed a visual version of the task. It was shown that the Braille tactile working memory (BrWM) of CBS individuals under articulatory suppression is as efficient as that of sighted individuals’ visual working memory in the same condition. Moreover, the results suggest that BrWM may be more robust in the CBS than in the BRV subjects, thus pointing to the potential role of visual experience in shaping tactile working memory. A second experiment designed to assess the nature (spatial vs. verbal) of this working memory was then carried out with two new CBS and BRV groups having to perform the Braille task concurrently with a mental arithmetic task or a mental displacement of blocks task. We show that the disruption of memory was greatest when concurrently carrying out the mental displacement of blocks, indicating that the Braille tactile subsystem of working memory is likely spatial in nature in CBS. The results also point to the multimodal nature of working memory and show how experience can shape the development of its subcomponents.

Introduction

There has been an increasing interest in the study of blindness and its effects on cognition and behavior in recent years. An ongoing debate regarding whether blind individuals are able to compensate for their sensory handicap by developing exceptional abilities in their remaining senses [compensatory hypothesis: see 1], or by becoming severely handicapped given the importance of the visual modality in calibrating other senses [the deficit hypothesis: see 2] has yielded contrasting positions. While the results of a few studies have actually loaned support to the latter hypothesis [e.g., 3–5], the vast majority of published reports either support the former hypothesis or do not show any difference between sighted and blind individuals [for reviews, see 6–8]. Thus, the general view that blind individuals can exhibit enhanced abilities within their remaining senses. Although most of the early interest with blind individuals was with regards to their perceptual abilities in the auditory [9–12] and tactile [10,13–18] domains, there has been a growing shift with respect to language [19,20] and memory [17,21–26] functions.

Although tactile and memory functions in blind individuals have received much attention, little is known about the existence of a tactile subsystem within the framework of the most generally accepted model of working memory proposed by Baddeley and Hitch [27–30]. Briefly, this model consists of separate but interconnected subsystems, the most important of which is the central executive, which controls processes including access to the other subsystems as well as the retrieval of information stored in long-term memory. The other subsystems or modules are essentially “slave” systems, one of which is specialized for auditory-verbal and the other for visual stimuli. The verbal system contains a phonological store where verbal input is actively represented. These representations are maintained by subvocal rehearsal in a phonological loop which, when blocked, leads to impaired recall of information. The second “slave” system, also known as the visuospatial sketch pad, is argued to be responsible for storing visuo-spatial information and creating and manipulating mental images. Though the original model only proposed components for the auditory (phonological store) and visual (visuospatial sketchpad) modalities, the results from several studies rather suggest that working memory processes extend to other sensory modalities such as touch [31–36]. In fact, behavioral studies have shown that visual perception is not essential for an efficient development of working memory [25,26], suggesting that other sensory modalities might compensate by providing the necessary spatial information.

In light of the important contribution of tactile input for information processing in the blind, the purpose of this study was to further explore tactile working memory for Braille in this group of individuals via two experimental procedures. The first experiment was an immediate serial recall task with and without articulatory suppression and was carried out in order to determine
how this tactile working memory in blind subjects compared to visual working memory in sighted individuals, and secondly, to determine the extent to which the nature of the visual impairment (completely blind subjects (CBS) versus blind subjects with residual vision (BRV)) had any effect on its development. The second experiment was then designed to test if this tactile component of working memory was more spatial or verbal in nature by having new groups of participants perform the task concurrently with a mental arithmetic or a mental displacement of blocks task.

Methods

Subjects

All participants gave written and informed consent. Subjects were excluded if they had any brain damage or other neurological illness. The twelve sighted subjects were recruited from the Université de Quebec personnel and matched as closely as possible with two visually impaired groups (CBS and BRV) with respect to age, sex and education. The CBS and BRV subjects were equivalent in Braille fluency; all had a good command of the Braille alphabet, as assessed in a pre-test, with a minimum of 14 years of practice. All visual deficits were congenital.

Experiment 1 (Tactile task). Twenty-seven subjects (aged from 18 to 60 years) participated in this experiment. Fifteen subjects had a congenital visual deficiency, 7 with total blindness (CBS: completely blind subjects) and 8 with some residual vision (BRV: blind with residual vision) and 12 had normal vision (see Tables 1 and 2). The CBS subjects had a mean age of 44.14 years (ranging from 31 to 53) and the BRV subjects had a mean age of 45.03 (ranging from 41 to 53). The mean age of the control subjects was 44.6 years. The BRV group was composed of individuals who were classed as visually handicapped by the Centre de Recherche Interdisciplinaire en Readaptation Nazareth and Louis Braille, where the research originated.

Experiment 2 (Braille letter task). Two other groups made up of nine CBS subjects with a mean age of 40.11 (ranging from 25–53 years), (see Tables 3 and 4) and 11 BRV subjects with a mean age of 48.09 (ranging from 24–58 years) participated in this experiment. These were different groups of subjects from those who participated in Experiment 1, since the ethics committees of the Institut Nazareth and Louis Braille, the agency that looks after the well-being of visually handicapped individuals in Quebec, does not condone the repeated use of the same subjects for research purposes. The study was also approved by the Ethics Committee of Université du Québec, where the research originated.

Tasks

Experiment 1 (Tactile task). This was an immediate serial recall task with and without articulatory suppression. The task consisted of eight series each containing two sequences of stimuli. The number of stimuli in a sequence was then increased by one with each new series (starting with two in the first series and ending with nine in the last series). The stimuli were consonants (Braille characters) presented at the rate of one per second on a Braille board. The consonants were randomly selected, and any well-known acronyms were omitted. Articulatory suppression consisted of repeating aloud the syllable/b/a during the presentation of the Braille stimuli.

A visual analogue of this tactile task was also presented to the sighted and the BRV subjects (the latter also performed the task in its tactile form). The purpose of this task was first to verify the efficacy of the articulatory suppression task in sighted subjects and to assess the visual working memory of BRV subjects. Consonants (alphabet letters) were presented at a rate of one per second on a computer screen. The order of presentation of the tasks (tactile and visual) to the BRV subjects was counterbalanced.

Experiment 2 (Braille letter task). This task was a recognition task where consonants were presented at a rate of one every three seconds on a Braille board and consisted of eight

| Table 1. Description of completely blind subjects (CBS; Experiment 1). |
|---------------------|-----|-----|-----------------|-----------------|
| Subjects | Sex | Age | Education | Aetiology |
| 1 | F | 47 | 14 | Keropathy and glaucoma |
| 2 | M | 31 | 15 | Retinal detachment |
| 3 | M | 48 | 15 | Congenital cataracts and glaucoma |
| 4 | M | 50 | 19 | Retinal pigmentation |
| 5 | F | 53 | 20 | Retinal pigmentation |
| 6 | M | 34 | 19 | Congenital anophthalma |
| 7 | F | 46 | 18 | Congenital blindness (cause unknown) |

| Table 2. Description of blind subjects with residual vision (BRV; Experiment 1). |
|---------------------|-----|-----|-----------------|-----------------|
| Subjects | Sex | Age | Education | Aetiology |
| 1 | F | 47 | 11 | Congenital cataracts |
| 2 | F | 41 | 17 | Oculocutaneous albinism |
| 3 | F | 51 | 20 | Congenital cataracts |
| 4 | M | 42 | 20 | Oculocutaneous albinism |
| 5 | M | 44 | 18 | Congenital cataracts and glaucoma |
| 6 | F | 45 | 16 | Congenital cataracts |
| 7 | F | 53 | 13 | Oculocutaneous albinism |
| 8 | F | 42 | 16 | Bilateral lenticular ectopia |

| Table 3. Description of CBS (Experiment 2). |
|---------------------|-----|-----|-----------------|-----------------|
| Subjects | Sex | Age | Education | Aetiology |
| 1 | F | 25 | 18 | Tapeto-retinal degeneration |
| 2 | M | 29 | 16 | Retinal nerve atrophy |
| 3 | M | 52 | 19 | Retinal pigmentation |
| 4 | M | 33 | 16 | Retinal detachment and congenital cataracts |
| 5 | F | 35 | 18 | Retinal pigmentation |
| 6 | M | 50 | 15 | Congenital cataracts and glaucoma |
| 7 | F | 48 | 18 | Congenital blindness (cause unknown) |
| 8 | F | 34 | 14 | Retinal pigmentation |
| 9 | F | 55 | 20 | Retinal pigmentation |
of two tries for the first experiment, and out of three for the second. **The first experiment** was an immediate serial recall task with and without articulatory suppression. The results of CBS subjects on the Braille task were then compared to the performance of both BRV and sighted subjects on a visual version (see Methods) of the task. A two (task) by two (group) repeated measures ANOVA revealed both significant task ($F = 59.68$, $p < 0.001$) and group ($F = 4.57$, $p = 0.05$) effects confirming that the task is more difficult under articulatory suppression and that the CBS showed better performances than the BRV subjects overall across both tasks. Although the group by task interaction did not reach statistical significance ($F = 0.48$, $p > 0.05$), as it can clearly be seen in Figure 1, the group difference is essentially attributable to the CBS performing better than the BRV subjects under articulatory suppression, as revealed by a post-hoc contrast analysis ($p = 0.009$). The difference between the two groups when articulatory suppression is not present did not reach significance ($p = 0.385$).

Noteworthy is the fact that no difference was revealed when comparing tactile working memory of CBS subjects with the visual working memory of BRV and sighted control subjects under articulatory suppression ($F = 1.127$, $p > 0.05$) (see Figure 2). These findings indicate that it is likely that blind subjects (CBS) have a short-term memory specific for tactile stimuli which is in effect equivalent to the short-term memory for visual stimuli possessed by subjects with partial (BRV) or full sight.

**The second experiment** compared the performance of a different group of CBS subjects on three different tasks to assess if the tactile module was more spatial or verbal in nature (see Figure 3). The first was a simple serial recall of Braille consonants (B). The second consisted of the same task performed concurrently with a mental arithmetic task (that is, with a verbal component-BMA) and the third task was performed concurrently with a mental displacement of blocks (that is, with a spatial component-BMDB). A two (group) by three (task) ANOVA with repeated measures ANOVA revealed both significant task ($F = 59.68$, $p < 0.001$) and group ($F = 9.24$, $p = 0.007$) effects as well as a task by group interaction ($F = 9.40$, $p = 0.003$). The group

---

**Table 4.** Description of BRV subjects (Experiment 2).

| Subjects | Sex | Age | Education | Aetiology            |
|----------|-----|-----|-----------|----------------------|
| 1        | M   | 52  | 22        | Oculocutaneous albinism |
| 2        | F   | 51  | 17        | Oculocutaneous albinism |
| 3        | M   | 47  | 19        | Retinal nerve atrophy   |
| 4        | M   | 53  | 18        | Congenital cataracts    |
| 5        | M   | 44  | 17        | Congenital malign myopia |
| 6        | F   | 57  | 11        | Congenital cataracts    |
| 7        | M   | 58  | 19        | Congenital cataracts    |
| 8        | M   | 49  | 17        | Leber’s disease         |
| 9        | M   | 37  | 17        | Leber’s disease         |
| 10       | F   | 57  | 12        | Congenital cataracts    |
| 11       | F   | 24  | 12        | Leber’s Amaurosis       |

---

**Results**

The scores obtained by each subject was the maximum number of items recalled for which the subject succeeded at least once out
difference is mainly attributable to the CBS better performing the arithmetic task than the BRV subjects as demonstrated via a post-hoc contrast analysis (p<0.001). No other comparisons between the two groups reached statistical significance (p>0.05) — although the two groups probably differ with regards to their ability to perform the Braille task alone, as a strong ceiling effect was observed for the CBS subjects. Further post-hoc contrast analyses revealed that all tasks were significantly different from one another for both groups (p<0.001), demonstrating not only that the mental arithmetic task and the mental displacement of blocks task significantly reduced performance compared to the Braille task alone, but also that the interference caused by the mental displacement of blocks task was significantly greater than that caused by the mental arithmetic task.

The latter result also suggests that BrWM is more robust in individuals with complete visual deprivation than in those with partial vision. One possibility is that individuals are born with similar levels of short-term memory capacity for the different sensory modalities but, depending on sensory experience, some memory modalities become more enhanced than others. Thus, most persons have good auditory and visual short-term memory, because they have the most experience with inputs in these modalities. Consequently, the working memory subsystems might be highly crossmodal with numerous interconnections, the strengths of which are altered through experience. To test this hypothesis the results of CBS subjects on the Braille task were then compared to the performance of both BRV and sighted subjects on a visual analogue (see Methods) of the task to assess whether the tactile working memory for Braille of the blind is of comparable capacity to the visual working memory of sighted individuals. Indeed the performance of the CBS in the tactile task was found to be very similar to that of the BRV and sighted subjects in the visual task under articulatory suppression, suggesting that in the absence of visual input, tactile processes of working memory can achieve the same level of efficiency as does vision in sighted people. Moreover, these results are in strong agreement with the findings of a previous study comparing working memory for Braille and a raised-letter tactile task in blind individuals with that of visual and a raised-letter tactile in sighted individuals [22]. While the performance for the raised-letter tactile working memory task was found to be superior in the blind, the performance of the blind in the Braille working memory task was shown to be equivalent to that of the sighted performing the visual task, again strongly suggesting that tactile Braille working memory in the blind is very comparable to visual working memory in the sighted.

This result is consistent with a recent finding showing that working memory processes in both visual and tactile modalities share common neural networks [35], thus providing support for the notion of a working memory system independent of sensory modality. Additional support for the idea of a multi-modal working memory system comes from Zhou and Fuster [38], who found that during a cross-modal (visuo-haptic) delayed-matching task, neurons in the somatosensory cortex fired in response to visual stimuli which were behaviourally associated with tactile information. This could also account for Deibert et al. ’s [39] findings that a tactile object recognition task elicited the participation of areas of the visual system as well as other brain areas in the somatosensory and motor systems of sighted subjects. Alternatively, one could argue that the comparable performance in both Braille and visual working memory may be a result of the use of similar verbal processes. This is an empirical question and it
could be assessed in future experiments using pseudo-Braille and visual pseudo-letter stimuli. An even more striking piece of evidence comes from studies showing that V1 [19] and the calcineurin tissue [21] are activated during reading and recuperation of Braille information from memory. As well, tactile working memory tasks activate the dorsal extrastriate visual stream in congenitally blind individuals [40], perhaps explaining why tactile working memory in blind individuals achieves similar levels of efficiency as visual working memory in sighted ones. Similarly, crossmodal recruitment of V1 is also observed in sighted individuals who have been blindfolded for several days [41], a condition that has also been shown to increase tactile performance in sighted individuals [42]. Perhaps even more striking is the finding that V1 is activated when trained experts in a specific type of tactile stimuli perform discrimination tasks with such stimuli [43].

The fact that the dorsal stream was preferentially activated also suggests that tactile working memory is subserved, at least in blind individuals, by areas specialized in spatial processing. This notion is in fact strongly corroborated by the results of our second experiment. Indeed the finding that the disruption of memory was greatest when concurrently carrying out the mental displacement of blocks for both CBS and BRV subjects compared to concurrently carrying out mental arithmetic tasks, strongly suggests that the tactile subsystem of working memory used for Braille is most likely spatial in nature.

Mental rotation is a complex cognitive task recruiting several brain areas, notably BA7a,b in the parietal cortex, probably because of the task requirement of encoding spatial relations and computing movement. Area V5 is also activated, probably a reflection of the task requirement of mentalizing the rotation of the object [44]. On the other hand, mental arithmetic activates the left occipital-temporal cortex (left supramarginal sulcus, BA40), the adjoining intraparietal gyrus (BA37/21) and the left anterior intraparietal sulcus (BA7) [45]. Thus, while it is true that both tasks have verbal components, especially since they both involve verbal instructions, there is little overlap between the neural networks involved. However, until there is a confrontation between both tasks with the same subjects, this conclusion remains to be confirmed.

Finally regarding the nature of Braille tactile working memory, it is clear that one must distinguish between verbal memory, verb generation and Braille. In the Arnedi et al. [21] study, only the last condition was associated with an activation of the right occipital cortex. This region thus appears to be specific to Braille in the early blind subjects. There is clearly, in these results, a distinction between Braille memory, verbal memory and verb generation, all verbal tasks. The question is, how does the activation of this area affect the encoding of the relevant information. The results of the present study show that the encoding is spatial in character. However, it is possible that the mental rotation task may be more difficult than the mental arithmetic task, and that might explain why the former was more efficient in blocking the working memory task.

In summary, tactile working memory for Braille in the blind was found to be as efficient under articulatory suppression as was visual working memory in sighted individuals. Moreover, articulatory suppression appeared to influence the tactile working memory of CBS more than that of BRV subjects, suggesting that visual experience may play a crucial role in shaping tactile working memory. Further research is required however to verify this assumption. The results of the second experiment indicate that tactile working memory in the blind has an important spatial component, suggesting that this component may be intact in these individuals despite the absence of visual input, a spatial function that is perhaps related to an overlearned ability, that is, Braille reading.

Acknowledgments

This paper is dedicated to the memory of Dr. Robert Viau, who contributed to all aspects of this study. We thank the participants as well as the Institut Nazareth et Louis-Braille (INLB) for their assistance in recruiting the blind subjects. The research protocols were approved by the ethics committees of the Centre de Recherche Interdisciplinaire en Réadaptation which coordinates research with blind subjects sponsored by the INLB, and by l'Université du Québec à Montréal, from which the project originated.

Author Contributions

Conceived and designed the experiments: HC PS. Analyzed the data: HC PV FL PS. Contributed reagents/materials/analysis tools: HC PS. Wrote the paper: HC PV FL PS. Supervised the conduct of the study: HC PS.

References

1. Rice CE (1970) Early blindness early experience and perceptual enhancement. Res Bull Amer Foundation for the Blind 22: 1–22.
2. Axelrod S (1999) Effects of early blindness: Performance of blind and sighted children on tactile and auditory tasks (Research Series No. 7). New York: American Foundation for the Blind.
3. Jones B (1975) Spatial perception in the blind. Brit J Psychol 66: 461–472.
4. Lewald J (2002) Vertical sound localization in blind humans. Neuropsychologia 40: 1868–1872.
5. Zwiers MP, Van Opstal AJ, Cruysberg JM (2001) A spatial hearing deficit in early blind individuals. J Neurosci 21: RC421 1–5.
6. Collignon O, Voss P, Lassonde M, Lepore F (2008) Adaptation to sensory loss. Wiley Interdisciplinary Reviews: Cognitive Science In press.
7. Alary F, Goldstein D, Duquette M, Chapman CE, Voss P, et al. (2008) Tactile acuity in the blind: a psychophysical study using a two-dimensional angle discrimination task. Exp Br Res 167: 567–94.
8. Burton H, Snyder AZ, Diamond J, Raichle ME (2002) Adaptive changes in early and late blind: a fMRI study of Braille reading. J Neurophysiol 87: 509–611.
9. Goldreich D, Kanics IM (2003) Tactile acuity is enhanced in blindness. J Neurosci 23: 3439–3445.
10. Rieder B, Rodier F, Neville HJ (2001) Auditory memory in congenitally blind adults: a behavioral-electrophysiological investigation. Br Res Cognitive Br Res 11: 289–303.
11. Sado N, Pascual-Leone A, Graeff M, Ibanez V, Deiber MP, et al. (1996) Activation of the primary visual cortex by Braille reading in blind subjects. Nature 380: 526–528.
12. Rieder B, Snyder AZ, Diamond J, Raichle ME (2002) Adaptive changes in early and late blind: a fMRI study of verb generation to heard nouns. J Neurophysiol 88: 3559–3571.
20. Röder B, Rosler F, Neville HJ (2000) Event-related potentials during auditory language processing in congenitally blind and sighted people. Neuropsychologia 38: 1482–1502.
21. Amedi A, Raz N, Pianka P, Malach R, Zohary E (2003) Early ‘visual’ cortex activation correlates with superior verbal memory performance in the blind. Nature Neurosci 6: 756–766.
22. Bliss I, Kujala T, Hamalaninen H (2004) Comparison of blind and sighted participants’ performance in a letter recognition working memory task. Br J Cognit Neuropsych 10: 271–277.
23. D'Anguille A, Warach P (2002) Enhanced tactile encoding and memory recognition in congenital blindness. Int J Rehabil Res 25: 143–145.
24. Röder B, Rosler F (2003) Memory for environmental sounds in sighted congenitally blind and late blind adults: evidence for cross-modal compensation. Int J Psychophysiol 50: 27–39.
25. Vecchi T (1998) Visuo-spatial imagery in congenitally totally blind people. Memory 6: 91–102.
26. Vecchi T, Tinti C, Cornoldi C (2004) Spatial memory and integration processes in congenital blindness. NeuroReport 15: 2787–2790.
27. Baddeley AD, Hitch GJ (1974) Working Memory. In: Bower GA, ed. Recent Advances in Learning and Motivation. London: Academic Press. pp 47–90.
28. Baddeley AD (1986) Working memory. London: Oxford University Press.
29. Baddeley AD (1992) Is working memory working? Quarterl J Exper Psychol A 44A: 1–31.
30. Baddeley AD (2001) Is working memory still working? Amer Psychologist 56: 831–864.
31. Cornoldi C, Vecchi T (2003) Visual-spatial working memory and individual differences. Hove: Psychology Press.
32. Gibson EQ, Baddeley AD (1969) Tactile short-term memory. Quarterl J Exper Psychol 21: 180–184.
33. Mahner P, Miles C (2002) Recognition memory for tactile sequences. Memory 10: 7–20.
34. Miles C, Borthwick H (1996) Tactile short-term memory revisited. Memory 4: 655–668.
35. Ricciardi E, Bonino D, Gentili C, Sani L, Pietrini P, et al. (2006) Neural correlates of spatial working memory in humans: a functional magnetic resonance imaging study comparing visual and tactile processes. Neuroscience 139: 339–349.
36. Sullivan EV, Turvey MT (1972) Short-term retention of tactile stimulation. Quarterl J Exper Psychol 24: 253–261.
37. Logie RH, Zucco GM, Baddeley AD (1990) Interference with visual short-term memory. Acta Psychologica 75: 55–74.
38. Zhou YD, Fuster JM (1997) Neuronal activity of somatosensory cortex in a cross-modal (visuo-haptic) memory task. Exp Br Res 116: 531–533.
39. Deibert E, Kraut M, Kremen S, Hart J, Jr. (1999) Neural pathways in tactile recognition. Neuro 52: 1413–1417.
40. Borino D, Ricciardi E, Sani L, Gentili C, Vanello N, et al. (2008) Tactile spatial working memory activates the dorsal extrastriate cortical pathway in congenitally blind subjects. Arch It Biol 146: 133–146.
41. Merabet LB, Hamilton R, Schlaug G, Swisher JD, Kirikopoulos ET, et al. (2008) Rapid and reversible recruitment of early visual cortex for touch. PLoS ONE 3: e3046.
42. Facchini S, Aghioti SM (2003) Short-term light deprivation increases tactile spatial acuity in humans. Neuro 60: 1998–1999.
43. Sato DN, Okada T, Honda M, Yonekura Y, Sadato N (2006) Practice makes perfect: the neural substrates of tactile discrimination by Mah-Jong experts include the primary visual cortex. BMC Neurosci 7: 79.
44. Cohen MS, Kosslyn SM, Breiter HC, DiGirolamo GJ, et al. (1996) Changes in cortical activity during mental rotation. A mapping study using functional MRI. Brain 119: 89–100.
45. Rivera SM, Reiss AL, Eckert MA, Menon V (2005) Developmental changes in mental arithmetic: Evidence for increased functional specialization in the left inferior parietal cortex. Cereb Cortex 15: 1779–1790.