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Report

Superior Serial Memory in the Blind: A Case of Cognitive Compensatory Adjustment

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Summary

In the absence of vision, perception of space is likely to be highly dependent on memory. As previously stated, the blind tend to code spatial information in the form of "route-like" sequential representations [1–3]. Thus, serial memory, indicating the order in which items are encountered, may be especially important for the blind to generate a mental picture of the world. In accordance, we find that the congenitally blind are remarkably superior to sighted peers in serial memory tasks. Specifically, subjects heard a list of 20 words and were instructed to recall the words according to their original order in the list. The blind recalled more words than the sighted (indicating better item memory), but their greatest advantage was in recalling longer word sequences (according to their original order). We further show that the serial memory superiority of the blind is not merely a result of their advantage in item recall per se (as we additionally confirm via a separate recognition memory task). These results suggest the refinement of a specific cognitive ability to compensate for blindness in humans.

Results and Discussion

This study compared the performance of 19 congenially blind subjects and individually matched sighted controls in two types of memory tasks: item memory and serial memory. Typically, in item memory tasks, subjects are requested to identify the items learned (i.e., which items were included in the learned list). In comparison, in serial memory tasks, subjects have to remember both the items learned and their ordinal position in the list (see review [4]). Subjects heard a list of 20 words and were instructed to recall the words according to their original order in the list. This is referred to as the recall task. List presentation followed by recall was repeated four times, enabling learning. After the second and fourth recall sessions, subjects were additionally tested on a recognition memory task (see Figure 1A; for further details, see Supplemental Experimental Procedures available online). Item memory and serial memory performance was estimated from *both* recall and recognition memory tasks.

Figure 1B shows the average item memory performance assessed from the recall task, during each of the four testing sessions (R_1–R_4). Item memory performance was defined as the number of items correctly recalled from the list, irrespective of the order of recall (indicated as "item"). As seen, the blind recalled significantly more words (20%–35% in the various recall sessions) compared to their sighted peers.

Figure 1C plots the recall probability for the various words according to their serial position in the list. This is shown for each of the four testing sessions of the recall task. Note that this analysis does not convey information about the order in which the items were recalled (see Supplemental Experimental Procedures and [5]). The resulting graph shows both a primacy effect and a smaller recency effect in both sighted and blind, in accordance with the standard serial position curve for serial recall [6, 7]. Overall, recall probabilities are higher in the blind across *all* item positions, but the serial position curves' structure is practically the same in the sighted and blind. Thus, it seems that the advantage of blind in item recall is not a result of a specific advantage in remembering the first words in the list, or the most recent words. Rather, the blind recall better all words, irrespective of their serial position. This suggests that the blind may represent item lists as chains of words, in their correct order ("chaining"), perhaps by generating associations between adjacent items [8–10]. Thus, recalling an item increases the probability of recalling its following item (in all list positions).

We now focus on serial memory performance in the recall task, during each of the four testing sessions. First, we present in Figure 2A the number of words recalled in *sequences* of correct order of presentation (of any length, indicated as "sequence"). As seen, the blind recalled markedly more words in sequences compared with their sighted peers (85%–135% more words in sequences, in the various recall sessions). Note that while the blind were superior to the sighted in both the number of items recalled (Figure 1B) and the number of items recalled according to their order of presentation (Figure 2A), their superiority was far greater in the latter case. To further address the differences between sighted and blind in item and serial memory, a 2 (groups) × 2 (memory type, i.e., item or serial) × 4 (testing sessions) repeated measures ANOVA was also computed. Main effects of group [$F(1,36) = 20.0$, $p < 0.001$] and memory type [$F(1,36) = 167.4$, $p < 0.001$] were found, as well as a significant main effect of session [$F(3,108) = 204.5$, $p < 0.001$]. We also found a significant interaction of group by memory type [$F(1,36) = 10.2$, $p < 0.005$], indicating that the advantage of blind over sighted differs in the two memory types. Finally, a significant interaction of group, memory type, and testing session [$F(3,108) = 6.0$,

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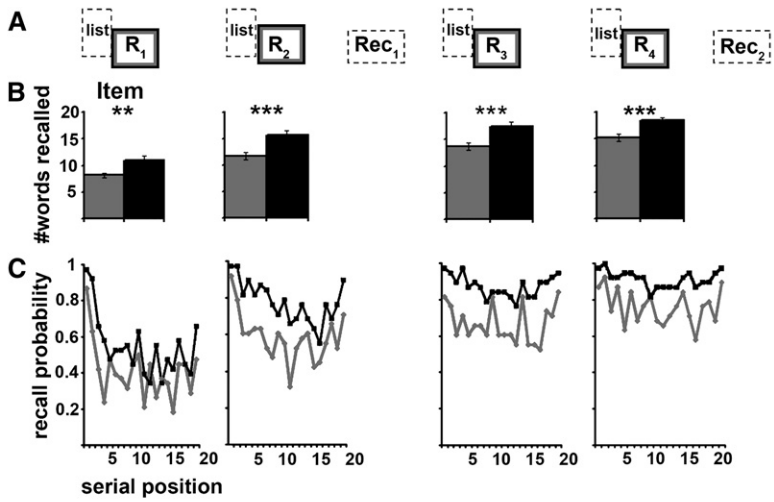

Figure 1. Item Memory Performance during the Recall Task

(A) Full experimental procedure, including recall (R) and recognition (Rec) tasks. Memory performance (shown in [B] and [C]) is assessed from the four sessions of the recall task (R_1–R_4). Performance is averaged within the blind (n = 19; black symbols) and sighted (n = 19; gray symbols) groups. The sighted controls matched the blind in their age, gender, and years of education on subject-by-subject basis.

(B) Item memory performance score (item) in the recall task. Asterisks denote significance level (in comparisons between the two groups; two-tailed paired t test, *p < 0.05; **p < 0.01, ***p < 0.001). Error bars denote SEM.

(C) Serial position curves, for each of the four sessions of the recall task, plotting recall probabilities for items in the various positions in the list.

$p < 0.05$] further indicated that the superiority of the blind in item and serial learning differs in the two memory types (see below).

One possible concern is that the superior serial memory of the blind stems directly from their advantage in item memory per se; perhaps the likelihood of recalling more words in sequences increases as more words are recalled. This possible confounding factor is addressed in the following analyses. First, Figure 2B presents the number of words recalled in sequences of various lengths out of the overall number of words recalled (therefore, adjusting for differences in item recall). The recall performance on each session was divided into four groups: the proportion of words recalled as single words; short sequences of 2–5 words; intermediate-length sequences of 6–10 words; and long sequences of 11–20 words. Note that from the second repetition onward, the blind recall more than half of the words in sequences. In comparison, the sighted still recalled at least half of the words as single words throughout the experiment (i.e., they failed to generate a sequence for at least half of the words they recalled). The superior serial memory of the blind is most pronounced when considering memory of long sequences. The proportion of long sequences increased drastically with repetitions in the blind, but not in sighted peers ($t = 4.3$, $p < 0.001$; $t = 1.8$, $p = 0.09$, respectively, when comparing the proportion of words recalled as part of long sequences in sessions 1 and 4; two-tailed paired t test).

We further tested whether the blind participants' superiority in serial memory is maintained after adjusting for differences in item memory performance levels. Compared with Figure 2B, we now control for both the *number* of items recalled and their *serial position* (in the list). Figure 2C plots the number of sequences of 2–20 words recalled in their correct order, out of the number of sequences that *could have potentially* been composed (from the actual recalled words, either in the current or previous sessions). This procedure makes sure that differences in serial memory (measured by the number of sequences recalled) are not merely due to differences in the specifically remembered words. As seen in Figure 2C, the serial memory superiority of the blind is still well established when taking into account differences in item memory. This means that, also when remembering the same specific items, the blind tend (more than sighted) to arrange them in sequences.

Third, we took advantage of the fortuitous fact that item memory performance of the blind in the second session of the recall task was practically the same as the item memory performance of sighted in the fourth session (see Figure 3A, "item"). Comparison of the two groups' serial memory performance in these sessions clearly demonstrates the superiority of the blind over the sighted (serial memory was assessed as "sequence," i.e., the number of words recalled in sequences, as in Figure 2A). The differences in serial memory performance between the two groups were statistically significant ($t = 2.6$, $p < 0.05$; two-tailed paired t test). We additionally compared memory performance in the sighted and blind by using a different memory task, the recognition task (Figure 3B). Subjects heard pairs of words and were requested to judge whether both words in a pair were part of the played list—item memory judgment (item-rec)—or whether the order of the words in the pair matched their order of presentation in the list—serial memory judgment (serial-rec). As mentioned before, the recognition task was done twice (immediately after the second and the fourth repetitions of the recall task). Mirroring the results in the recall task, item memory performance of blind in the first session of the recognition task was almost the same as that of sighted in the second session (item-rec: 93.7% versus 96.3% of correct responses, respectively, two-tailed paired t test $t = 1.0$, $p = 0.31$; corresponding $d' = 1.7, 2.1$ for blind and sighted, respectively). Yet, the blind were significantly better at the serial-rec task (91.4% versus 82.8% correct responses, $t = 2.8$, $p < 0.05$; $d' = 1.7, 1.2$ for blind and sighted, respectively). Once again, serial memory superiority in the blind was maintained in conditions at which item memory performance was equal. Because the superior serial memory of the blind was demonstrated by different methods of data analysis and memory tasks (recall and recognition) in which differences in item memory were abolished (or taken into

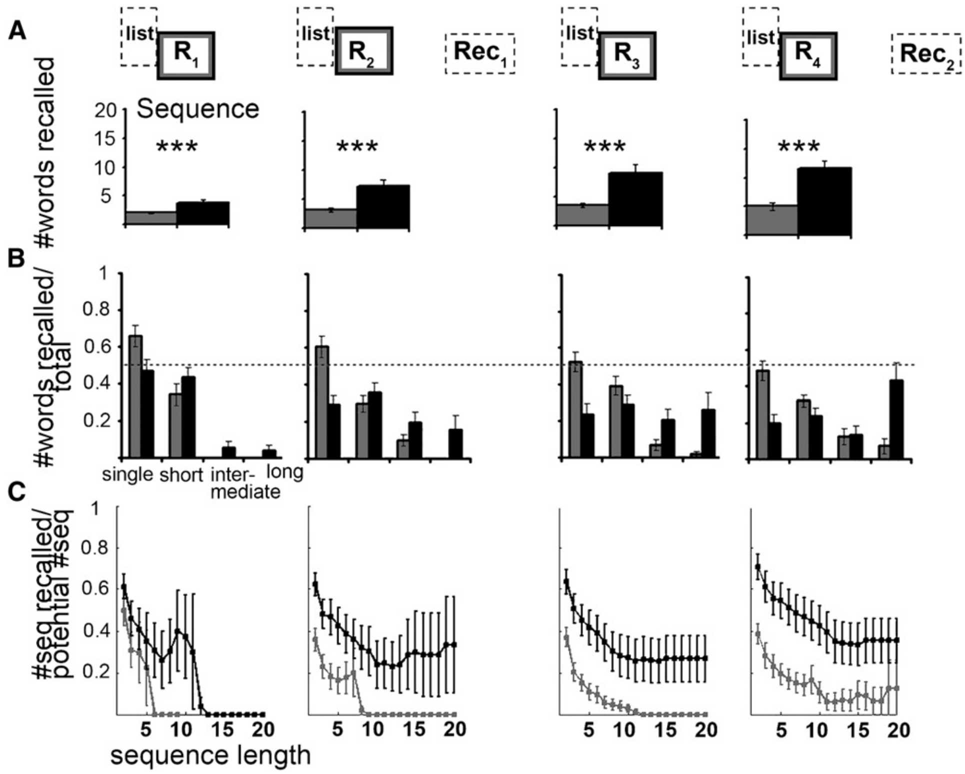

Figure 2. Serial Memory Performance during the Recall Task

Black and gray symbols indicate the averaged memory performance of the blind and sighted, respectively, in each session of the recall task (R_1–R_4).

(A) Serial memory performance is assessed by the sequence score, i.e., the number of words recalled in sequences (of any length). Asterisks as in Figure 1.

(B) The number of words recalled in sequences of various lengths out of the overall number of words recalled. Recall performance was divided into four groups: the proportion of words recalled as single words; as short sequences of 2–5 words; intermediate-length sequences of 6–10 words; and long sequences of 11–20 words. For example, when recalling a total of eight words in the following order, #1, 2, 3, 4, 8, 5, 19, 20 (where numbers denote the word's serial position in the list), 0.75 of the words were recalled as short sequences (words #1–4 and words #19–20) and 0.25 were recalled as single words, disjointly from adjacent words in the list (words #5, 8). Dashed line indicates a proportion of 0.5.

(C) The number of sequences recalled, relative to the number of sequences that could have potentially been composed (i.e., sequences whose individual words were recalled). Thus, if a subject recalled words #1, 2, 3, 4, 8, 5, 19, 20, the score for a 4-word sequence is 0.5, because the subject recalled one of two possible 4-words sequences; (#1, 2, 3, 4, but not 2, 3, 4, 5). This measure was calculated separately for all sequence lengths (i.e., sequences composed of 2–20 words). Error bars denote SEM.

account), we safely conclude that it was not a result of the blind subjects' advantage in item representation per se.

Next, we focus on item and serial *learning* (across the testing sessions of the recall task), as indicated by the learning curves (Figure 4). Item learning was defined as the total number of items recalled, across sessions, irrespective of the order of recall (Figure 4A, replotting the data from Figure 1A). Serial learning was assessed with different scores (the first is an elementary requirement and the latter two are stricter): (1) relative order score (Figure 4B), the number of items recalled in the correct general order (after an earlier but not necessarily adjacent item) [7, 11]; (2) sequences score (Figure 4C), the number of items recalled in sequences (replotting data from Figure 2A); and (3) positional order score (Figure 4D), the number of items recalled in their correct ordinal position [7, 11]. The results are clear: although the blind have an advantage over their sighted peers in both item learning and serial learning, the superiority of the blind is greater for the latter. This is even more pronounced when the serial learning score is based on stricter serial demands (compare Figures 4C and 4D with Figure 4B), and is maintained when controlling for individual differences in item memory levels (Figures 4E–4G).

Finally, in order to examine the trial-by-trial gains and losses of both item and order information, we adopted the analysis devised by Addis and Kahana [11], which differentiates between these elements during learning (see [11] for detailed information). First, our sighted subjects' performance was comparable to that of their "good" learners, providing further evidence that the superior performance of the blind (in our study) was not simply due to poor performance of our sighted controls (Figure S3). Second, it verified that the blind are superior to the sighted in their rate of order information acquisition (see Figures S2 and S3). This analysis further confirms that the advantage of the blind in serial learning is even more pronounced when the score is based on stricter serial demands (compare Figures S2 and S3).

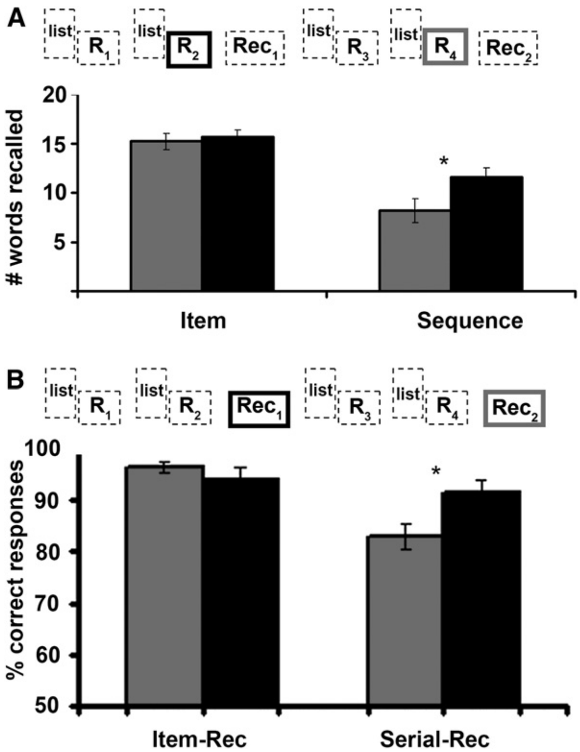

Figure 3. Serial Memory Performance of the Blind and Sighted in Equal Item Memory Conditions

Black and gray symbols indicate the averaged memory performance of the blind and sighted, respectively.

(A) All results shown are from the second session of the recall task for the blind (R_2) and from the fourth session for the sighted (R_4), having roughly the same item memory performance (left column; "item"). Left, the number of words recalled (item); right, the number of words recalled in sequences (sequence).

(B) Recognition memory performance measured as the percent of correct responses (Item-Rec and Serial-Rec, for item and serial memory judgments, respectively). These were assessed during the first session of the recognition test (Rec_1) in the blind and the second session (Rec_2) in the sighted. Note that in both tests (recall and recognition), no statistically significant differences appear in item memory, but there are substantial differences in serial memory between the sighted and the blind. Asterisks as in Figure 1. Error bars denote SEM.

Superior performance in the blind was previously demonstrated with various memory tasks. Congenitally blind people were better than their sighted peers in a long-term item recognition task with aurally presented words [12–14] and environmental sounds (such as a dog's bark [15]). Several studies [16–19] have shown longer short-term memory spans in the blind in tasks that require recall of items in their correct order, such as the digit-span or the word-span task. This task requires the recall of increasingly longer lists of items (2–9) according to their original order, until an error is made. Thus, the task incorporates both item and serial memory requirements. However, because errors in either item elements (i.e., digit insertion or deletion) or in serial position end the test, thereby determining the subject's memory span, it is impossible to infer from the existing literature whether the superior performance of blind was mainly due to their advantage in serial or item memory. Our results are the first to show that the blind subjects' greatest advantage is in *serial* memory and learning (when carefully taking into account differences in item memory performance). This superiority is seen both in the overall serial information acquisition and the amount of information acquired per trial.

Why do blind people have specific advantage in serial memory acquisition? Sighted people mostly code spatial information in the form of a global, externally based representation (i.e., maps or surveys, see [2, 3]). In contrast, as Millar [1] noted, the blind tend to code spatial information (especially of large spaces) in the form of a local, *sequential representation* based on routes [20]. This may be a natural consequence of the fact that the path traveled by a blind person cannot be apprehended at a glance (e.g., from a mountaintop) but rather must be constructed serially out of segmented inputs from each location along the path [21]. The blind also seem to adopt a serial strategy when encountered with a (small-scale) spatial imagery task [22], compared with a more global map-like representation of the sighted.

Another situation that requires extensive use of serial memory strategies by the blind is the identification of objects that are distinguishable from one another only by their visual properties (such as different brands of yogurts that differ only in their color or written tag). According to their own reports, in order to correctly choose a desired item, the blind typically place such items in a fashioned order and give them ordinal tags, such as "the third item on the left" (thus, they use verbal labeling to define ordinal relationships among items within the scene). We speculate that this may be a classical case of "practice makes perfect:" because the blind constantly use serial memory strategies in everyday circumstances, they develop superior serial memory skills that can also be used when required to recall a list of words, as in the present study.

Serial memory skills can be based on several strategies. Among them are the chaining and ordinal position accounts (see [23, 24] for reviews). Chaining assumes that serial learning is based largely on the formation of association between adjacent items [8–10]. Remote associations (between nonadjacent items) may also play an important, although secondary, role in serial learning [9]. In contrast, ordinal position accounts suggest that items are recalled in their order of presentation by the generation of an association between each item and its position in the list [25, 26]. Our current results indicate that the blind may have an advantage in the use of both strategies: chaining (see Figures 4C and 4F) and ordinal position (Figures 4D and 4G). However, a direct comparison between these two strategies in the blind should be tested by an explicit experiment.

To summarize, we show here that the congenitally blind are better than their sighted peers in both item memory and serial memory. However, the blind subjects' superiority is far greater in serial memory and in serial learning. Notably, the superior serial memory of the blind is not a result of their advantage in item recall per se and is apparent in both short-term (i.e., in the first session of the recall task) and long-term (as assessed by the improvement across the sessions of the recall task and by the recognition task) aspects of memory. We argue that this advantage is likely to be due to practice,

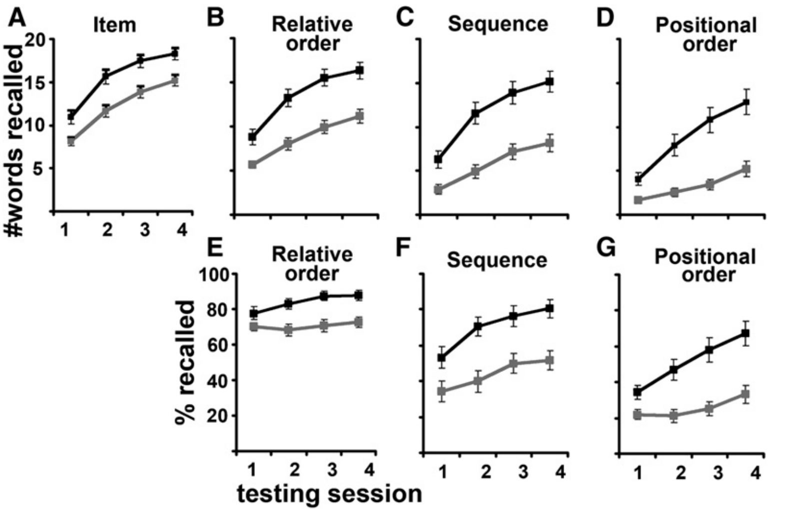

Figure 4. Item and Serial Learning in the Recall Task

Black and gray symbols indicate the averaged performance of the blind and sighted, respectively. Learning curves for the recall tasks: (A) item memory (item), the number of items recalled. Serial memory: (B) relative order, the number of items recalled in a correct relative order; (C) sequence, the number of items recalled in sequences; and (D) positional order, the number of items recalled in their correct ordinal positions. (E) The number of items recalled in a correct relative order, out of the overall number of words recalled. (F) The number of items recalled in correct sequence, out of the overall number of words recalled. (G) The number of items recalled in a correct positional order, out of the overall number of words recalled. Error bars denote SEM.

because the blind typically adopt serial strategies in order to compensate for the lack of immediate visual information. In this sense, our results are an example of a use-dependent plasticity.

Supplemental Data

Three figures, three tables, and Experimental Procedures are available at http://www.current-biology.com/cgi/content/full/17/13/1129/DC1/.

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