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Time, Space and Memory for Order

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ABSTRACT

Information about the order of items in a sequence can be conveyed either spatially or temporally. The current investigation examines whether these different modes of presentation map onto compatible mental representations of serial order. We examined this issue in three immediate serial recall experiments, in which participants recalled lists of letters in the temporal order they appeared. Each letter in a to-be-remembered sequence was presented in a unique spatial position, with the order of these spatial positions progressing from either left-to-right or from right-to-left. In this way, the visually presented lists contained both temporal and spatial order information. Recall of temporal order information was more accurate with congruent spatial order information – when the letters progressed from left-to-right, following the typical reading direction of English – compared to when the spatial order information was incongruent. These results suggest compatible representations of serial order when sequences are conveyed spatially and temporally.

Keywords: Serial order, temporal processing, spatial processing, immediate serial recall

Information about the order of items in a sequence can be conveyed either spatially or temporally. A comic strip read in the paper and a cartoon watched on television may convey the same order of events, but the former relies on spatial information, while the latter on temporal information. Some evidence suggests that the mental frameworks for representing temporal and spatial order enjoy a natural compatibility. When participants have to remember both spatial and temporal information about a short sequence of items, they respond faster and more accurately when those two dimensions convey similar order information than when they do not (e.g., Dutta & Nairne, 1993; Hitch, 1974). In a similar vein, when participants are asked to make a judgment about an item in temporally presented list, they respond more quickly with their left hand when making judgments about items that appeared towards the beginning, and more quickly with their right hands for items towards the end (Previtali, de Hevia & Girelli, 2010; Van Dijck & Fias, 2011). These correspondence effects are all consistent with a view in which representation of location in space (left vs. right, top vs. bottom) is compatibly represented, and thus interchangeable with, representation of temporal order information.

However, none of these results provide clear-cut evidence for this compatible representation view. Spatial-temporal congruence effects have primarily been reported in tasks in which participants only had to retrieve a single item; such tasks do not clearly tap into processes required for recall of order. Furthermore, these congruence effects are clearest in tasks that require both temporal and spatial information. When one of these dimensions is irrelevant for the task, congruence effects are reduced (Previtali, de Hevia & Girelli, 2010) or undetectable (Dutta & Nairne, 1993).

In the current study, we investigate whether spatially conveyed order information influences responses in a task that depends only on temporal order processing – immediate serial recall (ISR) of a list of visually presented letters. In this task, letters can be presented in unique spatial positions. If the spatial positions lie on a horizontal axis, for readers of English, they convey order information with the left-most item corresponding to the beginning of the sequence and the right-most to the end. This spatial order information can either be congruent with the temporal order information – when the sequence progresses from left to right – or incongruent – when the sequence progresses from right to left. This spatial order information is irrelevant for ISR. However, if compatible order representations are generated for spatial and temporal-presented sequences, recall of temporal order should be better with congruent spatial order information.

Such a result would be unanticipated by most theories of short-term memory, many of which assume phonological recoding and rehearsal (e.g. Baddeley & Hitch, 1974). Other theories allow for visuo-spatial information to influence serial recall (e.g. Nairne, 1990), but only by allowing spatial location to cue recall for the item identities. In our experiments, the two presentation directions are matched on visual distinctiveness, since each item appears in a unique screen position for both congruent and incongruent presentations. The conditions are thus equated for the visual distinctiveness of spatial cues, and provide a purer test of the compatible-representation hypothesis.

The compatible representation hypothesis makes predictions not only about recall accuracy, but also the types of errors that should be observed for congruent and incongruent lists. Specifically, with incongruent presentations, errors should be observed in which an item is recalled based on its spatial, not temporal, position (e.g., recalling the left-most item first, even

though it was the final item presented). We refer to these errors as *reflections*. Note, however, that the difference between the incongruent and congruent presentation directions should not only be due to reflections. Weaker item-order information in the incongruent condition may give rise to other types of errors, like other types of movement errors or even intrusion of items that didn't appear in the list (e.g., Henson, 1998).

Previous studies that have manipulated the spatial position of items during ISR have compared recall for centrally presented lists with either congruent spatial presentations (e.g., Battacchi, Pelamatti & Umiltà, 1990; Hitch & Morton, 1975; LeCompte, 1992), or presentations with random spatial positions (e.g., Healy, 1975; Li & Lewandowsky, 1995; McDowd & Madigan, 1991). Results have been mixed; while effects of spatially-distributed presentation have been reported for backward recall (Li & Lewandowsky, 1995) and for the recency portion of forward recall (Battacchi et al., 1990), most studies report no differences. Comparisons between central presentation and either congruent or random-position lists are not a straightforward test of the compatible representation hypothesis; because the items are spread out, congruent and random spatial position lists have greater visual distinctiveness than centrally presented lists. Furthermore, there may be encoding costs for random spatial position presentations, since participants cannot predict the location of the next item. Our paradigm controls for effects of visual distinctiveness and location predictability.

There is only one experiment that directly tests ISR for congruent and incongruent presentation directions. Chincotta et al. (1999, Experiment 3) had participants recall lists of numerals and number words with either congruent or incongruent spatial presentations and found greater memory span in the congruent condition. However, this experiment was limited by the

fact that memory span tasks require recall of an entire sequence. That procedure is thus unsuitable for testing predictions about serial position or types of errors.

Below, we report three experiments that examine the effect of spatial-temporal order congruence on ISR, with forward (Experiment 1), backward (Experiment 2) and post-cued recall direction (Experiment 3). Forward and backward recall depend on at least partially distinct retrieval mechanisms and comparisons across the two recall directions localize the level of representation at which these effects arise (e.g. Li & Lewandowsky, 1995). Post-cuing recall direction limits the effects of strategic factors during encoding and rehearsal (e.g. Hinrichs, 1968).

Experiment 1

Method

Participants

60 students (27 female) from University of Illinois participated in the study for extra course credit (Mean Age: 19.2, Range 18-28). All had normal or corrected-to-normal vision and were native English speakers.

Design and Procedures

Participants were shown lists of consonants and instructed to recall them in the temporal order in which they appeared. Each list was composed of 6 unique consonants drawn randomly from a pool of 18 consonants (Q and X were excluded). Each consonant was presented in one of six locations on the computer monitor. These locations were evenly spaced along a centered horizontal axis, half the width of the screen. The experiment was run in MATLAB 7.1 using the Psychophysics Toolbox and participants were tested in their own testing room.

Each trial started with an arrow in the center of the screen to cue the presentation direction, with “<” indicating a left-to-right trial and “>” indicating a right-to-left trial. Consonants were then presented singly, for 800 ms, in size 24 Arial font, with 200 ms of blank screen time between items, and with the screen position of each subsequent consonant progressing either left-to-right or right-to-left. Presentation direction varied randomly. One second after the final item disappeared, a vertical response box appeared on the screen, indicating that participants could initiate their response. The vertical response box ensured that item location during response did not match item location during presentation. Participants typed their response and hit enter to continue onto the next trial. In total, participants saw 6 practice lists (three congruent and three incongruent), followed by 90 experimental lists (45 congruent and 45 incongruent).

Results

Item accuracy was based on whether a consonant was recalled in its correct serial position. Overall, participants recalled 85.2% of the items correctly (86.2% with congruent and 84.1% with incongruent presentation). Figure 1 plots serial position curves by presentation direction. Table 2 shows the condition means by position as well as the between-subject standard errors for Experiments 1-3.

Accuracy results were analyzed using a multi-level logit model. The model was fit in the R software package (R Development Core Team, 2008) and Laplace estimation using the `glmer()` function of the *lme4* package. The dependent measure was the log odds of correctly recalling each item. Predictors included serial position, presentation direction and their interactions. Presentation direction was coded in the model using mean-centered contrast codes. Because serial position effects were expected to be non-linear, serial position was coded as a categorical

variable. Following the results of Battacchi et al. (1990), we used orthogonal planned contrasts to evaluate whether the congruence effects were larger at later serial positions. Specifically, we contrast-coded serial position using Helmert coding, a scheme in which the effect at one level of an ordinal factor is contrasted with the mean of all previous levels. The maximal random effect structure justified by our sample included random slopes of presentation direction for both participants and items. The significance of the presentation direction effect was assessed via likelihood-ratio tests comparing a full model with the presentation direction and interactions as fixed effects to a baseline model without them (Barr, Levy, Scheeper & Tily, 2013). This test accounts for the number additional parameters in the full model, and does not depend on how we chose to code serial position.

The full model that included fixed effects of presentation direction and interaction with serial position fit the data significantly better than the baseline model with only a fixed effect of serial position ($\chi^2(6) = 19.7, p < .01$). Table 1 displays parameter estimates for the full model. While there was no main effect of presentation direction, the odds of correctly recalling a consonant were 1.2 times greater with congruent presentation. Presentation direction interacted with serial position; specifically when position 5 was compared to positions 1-4 and when position 6 was compared to positions 1-5. The odds of accurate recall for the sixth item in the list was 1.4 times greater with congruent presentation, compared to only 1.1 times greater for the first five serial positions. None of the other interactions were significant.

Errors were categorized as intrusions, reflections, or other transposition errors. Table 3 displays errors rates for these different types. Overall intrusions (5.5%) and other transpositions (5.7%) were more common than reflections (3.6%). All error types were greater with incongruent presentation, but the difference was greatest with reflections: the odds of producing

a reflection was 1.5 times greater with incongruent presentation, compared to 1.1 times greater for intrusions and 1.0 times greater for other transpositions.

Figure 2 plots reflections as a function of serial position and presentation direction. With congruent presentation, there is an increase in these errors in the middle of the list, unsurprising given previous demonstrations that transpositions between nearby positions (3 and 4) are more common than transpositions between distant positions (1 and 6 or 2 and 5; Henson, 1998). More strikingly, there are more reflections with the incongruent presentation at all serial positions.

Discussion

In forward ISR, accuracy was affected by presentation direction, with congruent presentation leading to superior performance. This effect appears to be disproportionately driven by errors consistent with the compatible-representation hypothesis: an increase in reflections in the incongruent condition across all serial positions. Taken together, the accuracy and error-type results indicate that the order information conveyed by the location of items on the screen affects recall of temporal order information.

Though these results do not follow from a phonological-recoding position, we must be clear in stating that such results do not indicate the absence of such phonological codes. Instead it appears that spatial information continues to play a role in memory *in addition to this rehearsed phonological information*. Critically, spatial information does more than augment the visual distinctiveness of the component items. In this experiment, congruent and incongruent presentation directions were matched in terms of both the distinctiveness of the spatial locations and the predictability of where the next item is going to appear. Thus, this spatial information must convey information about the particular order of the items in the sequence, and that order

information is represented in such a way that it can either interfere with or enhance the order information conveyed by the timing of the presentation.

An additional finding from this experiment was that the effect of presentation direction is clearest in the recency portion of the serial recall curve, consistent with Battacchi et al. (1990). Recency effects can be accounted for by assuming that subvocal rehearsal serves as a strategy for retaining order information. The more an item is subvocally rehearsed, the more its recall relies on a phonological code and the less influence spatial information will have on recall. Since items towards the beginning of a list are rehearsed more, they are more likely to lose their associated spatial information, reducing the effect of presentation direction.

In Experiment 2, we looked for effects of presentation direction in backwards recall. While encoding and maintenance are argued to be shared between forward and backwards recall, the two tasks have been argued to differ in retrieval processes, with backwards recall potentially relying more on visuo-spatial cues (Li & Lewandowsky, 1995). Comparing the effects of presentation direction across these tasks will help localize the cognitive mechanism responsible for this effect.

Experiment 2

Method

Participants

60 students (33 female) from University of Illinois participated in the study for extra course credit (Mean Age: 19.2, Range 18-32). All had normal or corrected-to-normal vision and were native English speakers.

Design and Procedures

Design and procedures were identical to Experiment 1, except that participants were instructed to recall the letters in the reverse of the temporal order in which they were initially presented.

Results

Overall, participants recalled 80.2% of the items correctly (81.5% with congruent lists and 78.9% with the incongruent lists). Figure 3 plots serial position curves by presentation direction. The maximal random effect structure justified by our sample included random slopes of presentation direction for participants and random slopes of presentation direction, serial position and their interaction for items.

The full model fit the data significantly better than the baseline model ($\chi^2(6) = 12.6$, $p < .05$). Table 4 displays parameter estimates for the full model. The main effect of presentation direction was significant, with the odds of correctly recalling a consonant 1.2 times greater with the congruent condition. The interaction between presentation direction and serial position was significant, with a larger effect at position 6 than positions 1-5. None of the other interactions were significant.

Table 3 displays the distribution of error types. As with Experiment 1, reflections were the least common (4.0%, vs. intrusions: 7.7% and other transpositions: 8.1%). Yet, while all error types increased in the incongruent condition, the odds of producing a reflection increased the most (1.4 times greater in incongruent condition vs. intrusions: 1.1 times greater and other transpositions: 1.2 times greater). Figure 4 plots reflections as a function of presentation and direction and serial order. As in Experiment 1, the increase in reflections was observed at all positions.

Discussion

As with forward recall, the odds of correctly recalling an item in backwards recall was greater with congruent than with incongruent presentation. While the main effect of presentation direction was significant in Experiment 2, but not in Experiment 1, the odds of correct recall was equivalently affected (1.2 times greater) by congruent presentation in both experiments, suggesting that effect is not modulated by recall direction. Again, there was a disproportionately large increase in reflections across all serial positions with incongruent presentation, as predicted by the compatible representation hypothesis. Finally, this effect is larger in the recency portion of the serial position curve, consistent with the account that subvocal rehearsal processes limit the effect for earlier list items.

If the recency effect observed in Experiments 1 and 2 is due to a subvocal rehearsal strategy, then when that strategy is disrupted, larger congruency effects should be observed without the interaction with serial position. In Experiment 3, we disrupted the use of these rehearsal strategies by indicating recall direction to participants only after the entire list had been presented. (e.g. Hinrichs, 1968; Li & Lewandowsky, 1995).

Experiment 3

Method

Participants

60 students (39 female) from University of Illinois participated in the study for extra course credit (Mean Age: 19.1, Range 18-23). All had normal or corrected-to-normal vision and were native English speakers.

Design and Procedures

Design and procedures were identical to Experiments 1 and 2 with several key exceptions. First, participants saw 8 practice and 120 experimental lists, divided evenly between

forward and backward recall and congruent and incongruent presentation directions. Second, after the final item was presented, one of two words appeared in the center of the screen, “FORWARD” indicating forward recall and “BACKWARD” indicating backward recall.

Results

Overall, participants recalled 73.0% of the items correctly (75.1% with forward and 70.9% with backward recall; 76.8% with the congruent and 69.1% with the incongruent presentation). Figure 5 plots serial position curves by presentation and recall directions. For this experiment, the log odds of correct item recall were predicted by serial position, presentation and recall direction and their interactions. The maximal random effect structure justified by our sample included random slopes of presentation direction, recall direction, serial position and the interaction between presentation and recall direction for both participants and items.

The full model with the presentation direction and interactions as fixed effects fit the data significantly better than the baseline model ($\chi^2(12) = 21.4, p < .05$). Table 5 displays parameter estimates for the full model. Recall direction had a clear effect on accuracy, with the odds of recall 1.2 times greater for forward recall. Presentation direction also had a clear effect on accuracy, with the odds of recall 1.5 times greater in the congruent condition. None of the interactions were significant, except for a three-way interaction between presentation direction, recall direction and the final versus first five positions in the serial position function.

Table 3 shows the distribution of errors for congruent and incongruent presentation, collapsed across recall direction. Intrusions were the most frequent error type (11.1%), followed by other transposition (10.0%), with reflections being the least common (6.0%). However, the odds of producing a reflection error was 3.5 times greater in the incongruent condition, while the increase in the odds of producing intrusions (1.1) or other transposition errors (1.0) was much

less substantial. Figure 6 plots reflections by serial position and list type. The increase in reflections is observed at all serial positions.

Discussion

As with the two previous experiments, the odds of correctly recalling an item were greater for congruent lists. Furthermore, when rehearsal strategies were disrupted by post-cuing recall direction, the effect was larger for both forward and backward recall, and the interaction with serial position is reduced. This large effect again was primarily driven by a large increase in the number of reflections, as predicted by the compatible-representation hypothesis, though other error types increased as well.

General Discussion

The relative spatial positions of letters during presentation of a sequence affected participants' ability to recall their temporal order in ISR. Specifically, when the first letter appeared on the left side of the screen and each subsequent letter was presented farther to the right, recall was improved relative to a condition in which the first letter appeared on the right side of the screen and each subsequent letter was presented to the left. This result held regardless of the direction of recall (Experiment 1 vs. Experiment 2) and was more pronounced when participants could not anticipate recall direction during encoding (Experiment 3). In all three experiments, much of this effect was accounted for by reflections, in which the position of the item in the response was mirrored from its correct position. These errors were produced at all serial positions; there were errors in which the item was recalled in a position far from its correct position (e.g. recalling the first item last) and errors in which the item was recalled in a position adjacent to its correct position (e.g. recalling the third item fourth). In short, the three experiments demonstrate a replicable effect of spatial and temporal order congruence in ISR.

Such a pattern is difficult to reconcile with theories of verbal short-term memory that rely on the phonological loop (e.g. Baddeley & Hitch, 1974) and theories in which the visual distinctiveness of items influences the ease of recall (e.g. Nairne, 1990). Spatial information is lost in the phonological loop, and cannot influence recall. The congruent and incongruent presentation directions are matched for visual distinctiveness, so whatever advantages visual distinctiveness might have on the ability to recall an item should benefit both conditions.

It may be possible to interpret the accuracy data by assuming an encoding advantage with congruent presentation. By this account, because of reading experience, participants expect items to go from left to right and items are encoded more strongly when this expectation is met. However, this encoding advantage hypothesis cannot explain the error data. If the differences in accuracy were simply due to worse encoding in the incongruent condition, then the distribution of error types should be unaffected by presentation direction, and the disproportionate increase in reflections would not be expected.

Instead, we interpret these results as evidence for a cognitive mechanism that is compatible with both temporally and spatially conveyed order information. Items that appear earlier in time are represented as closer to the beginning of the sequence, as are items that appear further to the left. Spatial information influences temporal order representations even when the spatial position of the items is irrelevant for the task. Within this framework, congruent spatial information leads to a more robust representation of item order than incongruent spatial information. Figure 4 depicts the sequence of letters ABC with both the congruent and incongruent presentation directions, as well as the order representation of these two different presentations. Because the A in the congruent presentation appears both as the left-most letter and the first letter in time, it is strongly represented as being the first letter in the sequence. In

contrast, the A in the incongruent presentation is more weakly represented as the first letter in the sequence, as the relative spatial location of the A conveys the information that it is the final letter. Because position is double coded with incongruent presentations, reflections are predicted. Thus this account explains both the accuracy and the error data.

While spatial/temporal congruence effects were observed in all three experiments, the size of these effects and their interactions with serial position depended on the type of recall. The largest effects were observed in Experiment 3, in which participants could not predict recall direction during encoding. Furthermore, the size of the congruence effect interacted with serial position in Experiments 1 and 2, but not in Experiment 3. We account for these results by assuming that post-cuing recall direction disrupts subvocal rehearsal strategies (e.g. Hinrichs, 1968). The subvocal rehearsal strategy used in Experiment 1 and 2 masks a larger effect of spatial order information, especially for earlier list items, by increasing the role of phonological codes that have lost all spatial information. When this strategy is disrupted by post-cuing recall direction (Experiment 3), a larger spatial-temporal order congruence effect is observed across the entire list.

We have assumed that the left-to-right presentation was the congruent condition because our participants read a left-to-right language, English. Additional research is required to test this assumption. However, the Chincotta et al. (1999) experiment described above provides some initial support. They had Hebrew-speaking participants recall of sequences of numerals (read left-to-right in Hebrew) and number words (read right-to-left in Hebrew) while varying the presentation direction. Congruence effects depended on reading experience, with memory span for numerals greater with left-to-right presentation, and with right-to-left presentation with number words. The effects reported above may simply reflect the fact that the stimuli used in our

experiments (letters) are typically experienced with spatial order information. Additional research is required to determine whether these same effects would be observed with stimuli without a familiar spatial arrangement.

Both temporal and spatial information can be used to convey the order of items in a sequence. The results presented here suggest that these different methods of presenting order are represented compatibly and are able to interact. One need only look at the spatial metaphors used when we talk about time – how your “best days are right in front of you,” for example – to see how spatial and temporal concepts map onto general notions of sequential order. It may be so easy to talk about time using spatial metaphors, and vice-versa, because time and space are processed by shared mechanisms.

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Table 1: Fixed Effect estimates for Multi-level logit model of recall accuracy in Experiment 1

Fixed Effect	Coefficient	SE	Wald z	P
(Intercept)	2.21	.19	8.93	<.001
Presentation Direction	.15	.14	1.02	.31
Pos 1 vs. Pos 2	-.36	.04	-8.90	<.001
Pos 1 & 2 vs. Pos 3	-.44	.04	-10.82	<.001
Pos 1, 2 & 3 vs. Pos 4	-.54	.04	-13.96	<.001
Pos 1,2,3 & 4 vs. Pos 5	-.70	.04	-18.97	<.001
Pos 1,2,3,4 & 5 vs. Pos 6	-.48	.22	-12.87	<.001
Pos 1 vs. Pos 2 $\times$ Presentation Direction	-.02	.08	-.29	.77
Pos 1 & 2 vs. Pos 3 $\times$ Presentation Direction	-.03	.08	-.33	.74
Pos 1, 2 & 3 vs. Pos 4 $\times$ Presentation Direction	.00	.08	-.00	.99
Pos 1,2,3 & 4 vs. Pos 5 $\times$ Presentation Direction	.16	.07	2.14	<.05
Pos 1,2,3,4 & 5 vs. Pos 6 $\times$ Presentation Direction	.28	.07	3.72	<.001

Table 2: Mean accuracy and the by-subject stand error of the difference between the congruent and incongruent conditions for all serial positions in Experiments 1-3

		Serial Position					
		1	2	3	4	5	6
Experiment 1	Congruent	93	89	87	84	81	83
	Incongruent	93	88	86	83	78	78
	<i>Standard Error</i>	<i>1.7</i>	<i>1.8</i>	<i>1.8</i>	<i>1.9</i>	<i>1.8</i>	<i>1.9</i>
Experiment 2	Congruent	80	74	75	80	87	94
	Incongruent	76	71	74	78	85	90
	<i>Standard Error</i>	<i>1.8</i>	<i>1.5</i>	<i>1.6</i>	<i>1.6</i>	<i>1.6</i>	<i>1.8</i>
Experiment 3 Forward	Congruent	88	81	80	75	72	77
	Incongruent	79	73	72	68	66	70
	<i>Standard Error</i>	<i>3.6</i>	<i>3.2</i>	<i>2.9</i>	<i>2.9</i>	<i>3.0</i>	<i>3.1</i>
Experiment 3 Backward	Congruent	70	66	67	74	82	90
	Incongruent	62	60	62	66	72	80
	<i>Standard Error</i>	<i>2.7</i>	<i>2.3</i>	<i>2.3</i>	<i>2.6</i>	<i>3.1</i>	<i>3.6</i>

Table 3: Error rate for intrusions, reflections and other transpositions in all three experiments

	Condition	Intrusion	Reflection	Other Transposition
Experiment 1	Congruent	5.2%	2.9%	5.7%
	Incongruent	5.7%	4.4%	5.8%
	<i>Odds Ratio</i>	<i>1.1</i>	<i>1.6</i>	<i>1.0</i>
Experiment 2	Congruent	7.5%	3.4%	7.5%
	Incongruent	7.9%	4.6%	8.6%
	<i>Odds Ratio</i>	<i>1.1</i>	<i>1.4</i>	<i>1.2</i>
Experiment 3	Congruent	10.5%	2.8%	9.8%
	Incongruent	11.6%	9.2%	10.1%
	<i>Odds Ratio</i>	<i>1.1</i>	<i>3.5</i>	<i>1.0</i>

Table 4: Fixed Effect estimates for Multi-level logit model of recall accuracy in Experiment 2

Fixed Effect	Coefficient	SE	Wald z	P
(Intercept)	1.72	.17	10.09	<.001
Presentation Direction	-.22	.09	-2.45	<.05
Pos 1 vs. Pos 2	-.17	.02	-5.08	<.001
Pos 1 & 2 vs. Pos 3	-.05	.03	-1.33	.18
Pos 1, 2 & 3 vs. Pos 4	.19	.03	4.06	<.001
Pos 1,2,3 & 4 vs. Pos 5	.67	.04	15.10	<.001
Pos 1,2,3,4 & 5 vs. Pos 6	1.24	.05	19.47	<.001
Pos 1 vs. Pos 2 $\times$ Presentation Direction	.02	.05	.37	.71
Pos 1 & 2 vs. Pos 3 $\times$ Presentation Direction	.11	.06	1.74	.08
Pos 1, 2 & 3 vs. Pos 4 $\times$ Presentation Direction	.02	.06	.26	.80
Pos 1,2,3 & 4 vs. Pos 5 $\times$ Presentation Direction	-.02	.08	-.15	.88
Pos 1,2,3,4 & 5 vs. Pos 6 $\times$ Presentation Direction	-.28	.10	-2.59	<.05

Table 5: Fixed Effect estimates for Multi-level logit model of recall accuracy in Experiment 3

Fixed Effect	Coeff	SE	Wald z	p
(Intercept)	1.26	.17	7.63	<.001
Presentation Direction	.48	.15	3.17	<.01
Recall Direction	.28	.08	3.59	<.001
Presentation Direction $\times$ Recall Direction	-.03	.09	-.35	.72
Pos 1 vs. Pos 2	-.19	.03	-5.72	<.001
Pos 1 & 2 vs. Pos 3	-.13	.04	-3.04	<.01
Pos 1, 2 & 3 vs. Pos 4	-.09	.04	-2.17	<.05
Pos 1,2,3 & 4 vs. Pos 5	.02	.05	.49	.62
Pos 1,2,3,4 & 5 vs. Pos 6	.42	.05	7.95	<.001
Pos 1 vs. Pos 2 $\times$ Presentation Direction	-.03	.05	-.56	.58
Pos 1 & 2 vs. Pos 3 $\times$ Presentation Direction	-.02	.05	-.40	.69
Pos 1, 2 & 3 vs. Pos 4 $\times$ Presentation Direction	.02	.05	.35	.72
Pos 1,2,3 & 4 vs. Pos 5 $\times$ Presentation Direction	.02	.06	.39	.70
Pos 1,2,3,4 & 5 vs. Pos 6 $\times$ Presentation Direction	.10	.06	1.58	.11
Pos 1 vs. Pos 2 $\times$ Recall Direction	-.18	.05	-4.00	<.001
Pos 1 & 2 vs. Pos 3 $\times$ Recall Direction	-.27	.05	-5.29	<.001
Pos 1, 2 & 3 vs. Pos 4 $\times$ Recall Direction	-.66	.05	-12.29	<.001
Pos 1,2,3 & 4 vs. Pos 5 $\times$ Recall Direction	-1.07	.06	-19.11	<.001
Pos 1,2,3,4 & 5 vs. Pos 6 $\times$ Recall Direction	-1.22	.06	-19.11	<.001
Pos 1 vs. Pos 2 $\times$ Recall Direction $\times$ Presentation Direction	.01	.09	.07	.94
Pos 1 & 2 vs. Pos 3 $\times$ Recall Direction $\times$ Presentation Direction	.05	.10	.42	.67
Pos 1, 2 & 3 vs. Pos 4 $\times$ Recall Direction $\times$ Presentation Direction	-.14	.11	-1.30	.19
Pos 1,2,3 & 4 vs. Pos 5 $\times$ Recall Direction $\times$ Presentation Direction	-.17	.11	-1.49	.14
Pos 1,2,3,4 & 5 vs. Pos 6 $\times$ Recall Direction $\times$ Presentation Direction	-.25	.13	-1.98	<.05

Figure Captions

Figure 1: Serial position curve for Experiment 1, forward serial recall of lists with congruent (solid lines) and incongruent (dashed lines) presentation directions.

Figure 2: Reflections as a function of serial position for Experiment 1, with congruent (solid lines) and incongruent (dashed lines) presentation directions.

Figure 3: Serial position curve for Experiment 2, backward serial recall of lists with congruent (solid lines) and incongruent (dashed lines) presentation directions. Position reflects input position rather than output position.

Figure 4: Reflections as a function of serial position for Experiment 2, with congruent (solid lines) and incongruent (dashed lines) presentation directions.

Figure 5: Serial position curve for Experiment 3, for both forward (black lines) and backwards (gray lines) serial recall of lists with congruent (solid lines) and incongruent (dashed lines) presentation directions. For backwards recall, position reflects input position rather than output position.

Figure 6: Reflections as a function of serial position for Experiment 3, for both forward (black lines) and backwards recall (gray lines) with congruent (solid lines) and incongruent (dashed lines) presentation directions.

Figure 7: Depiction of the representation of the order of letters for the temporal letter sequence ABC, with congruent and incongruent spatial presentation directions.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7