Psychon Bull Rev (2014) 21:1263–1271
DOI 10.3758/s13423-014-0604-7

BRIEF REPORT

Time, space, and memory for order

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Published online: 20 March 2014

Abstract Information about the order of items in a sequence can be conveyed either spatially or temporally. In the present investigation, we examined 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 in which they had 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 right to left. In this way, the visually presented lists contained both temporal and spatial order information. Recall of the temporal order information was more accurate with congruent spatial order information—that is, when the letters progressed from left to right, following the typical reading direction of English—than 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, whereas the latter relies 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 more quickly and accurately when those two dimensions convey similar order information then when they do not (see, 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 toward the beginning, and more quickly with their right hand for items presented toward the end (Previtali, de Hevia, & Girelli, 2010; van Dijck & Fias, 2011). These correspondence effects are all consistent with a view in which the 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 the 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 et al., 2010) or undetectable (Dutta & Nairne, 1993).

In the present study, we investigated whether spatially conveyed order information influences responses in a task that depends only on temporal order processing—that is, 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 leftmost item corresponding to the beginning of the sequence, and the rightmost item corresponding to the end. This spatial order information can be either 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

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ISR. However, if compatible order representations are generated for spatially and temporally 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 visuospatial 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 were matched on visual distinctiveness, since each item appeared in a unique screen position for both congruent and incongruent presentations. The conditions were thus equated for the visual distinctiveness of spatial cues, to provide a purer test of the compatible-representation hypothesis.

The compatible-representation hypothesis makes predictions not only about recall accuracy, but also about 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 on the basis of its spatial, not temporal, position (e.g., recalling the leftmost 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 be due only to reflections. Weaker item-order information in the incongruent condition may give rise to other types of errors, such as other types of movement errors, or even the intrusion of items that did not appear in the list (e.g., Henson, 1998).

Previous studies that have manipulated the spatial positions of items during ISR have compared recall for centrally presented lists with recall for lists given either congruent spatial presentations (e.g., Battacchi, Pelamatti, & Umiltà, 1990; Hitch & Morton, 1975; LeCompte, 1992) or presentations at random spatial positions (e.g., Healy, 1975; Li & Lewandowsky, 1995; McDowd & Madigan, 1991). The results have been mixed; whereas 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 have reported 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 do centrally presented lists. Furthermore, random spatial-position presentations may incur encoding costs, since participants cannot predict the location of the next item. Our present paradigm controls for effects of visual distinctiveness and location predictability.

Only one experiment has directly tested ISR for congruent and incongruent presentation directions. Chincotta, Underwood, Ghani, Papadopoulou, and Wresinski (1999, Exp. 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 in which we examined the effects of spatial–temporal order congruence on ISR, with forward (Exp. 1), backward (Exp. 2), and postcued (Exp. 3) recall directions. Forward and backward recall depend on at least partially distinct retrieval mechanisms, and comparisons across the two recall directions would localize the level of representation at which these effects arise (e.g., Li & Lewandowsky, 1995). Postcuing recall direction limits the effects of strategic factors during encoding and rehearsal (e.g., Hinrichs, 1968).

Experiment 1

Method

Participants A group of 60 students (27 female, 33 male) 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 six unique consonants drawn randomly from a pool of 18 (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 that was 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 from 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 the item location during presentation. Participants typed their responses and hit Enter to continue onto the next trial. In total, participants saw six 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, and Table 1 shows the condition means by position as well as the between-subjects standard errors for Experiments 1–3.

Accuracy results were analyzed using a multilevel logit model. The model was fit using 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 nonlinear, 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 was 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, Scheepers, & Tily, 2013). This test accounted for the number of additional parameters in the full model and did not depend on how we chose to code serial position.

The full model that included fixed effects of presentation direction and the 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 2 displays the parameter estimates for the full model. Although we found no main effect of presentation direction,

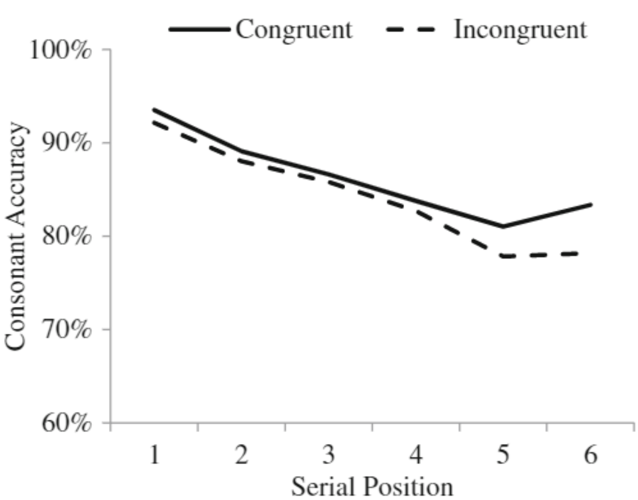

Fig. 1 Serial-position curves for Experiment 1, for forward serial recall of lists with congruent (solid line) and incongruent (dashed line) presentation directions

Table 1 Mean accuracy and the by-participants standard errors of the differences 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
	Standard Error	1.7	1.8	1.8	1.9	1.8	1.9
Experiment 2	Congruent	80	74	75	80	87	94
	Incongruent	76	71	74	78	85	90
	Standard Error	1.8	1.5	1.6	1.6	1.6	1.8
Experiment 3 Forward	Congruent	88	81	80	75	72	77
	Incongruent	79	73	72	68	66	70
	Standard Error	3.6	3.2	2.9	2.9	3.0	3.1
Experiment 3 Backward	Congruent	70	66	67	74	82	90
	Incongruent	62	60	62	66	72	80
	Standard Error	2.7	2.3	2.3	2.6	3.1	3.6

Table 2 Fixed-effect estimates for the multilevel logit model of recall accuracy in Experiment 1

Fixed Effect	Coefficient	*SE*	Wald *z*	*p*
(Intercept)	2.21	0.19	8.93	<.001
Presentation Direction	0.15	0.14	1.02	.31
Pos 1 vs. Pos 2	−0.36	0.04	−8.90	<.001
Pos 1 & 2 vs. Pos 3	−0.44	0.04	−10.82	<.001
Pos 1, 2 & 3 vs. Pos 4	−0.54	0.04	−13.96	<.001
Pos 1,2,3 & 4 vs. Pos 5	−0.70	0.04	−18.97	<.001
Pos 1,2,3,4 & 5 vs. Pos 6	−0.48	0.22	−12.87	<.001
Pos 1 vs. Pos 2 × Presentation Direction	−0.02	0.08	−0.29	.77
Pos 1 & 2 vs. Pos 3 × Presentation Direction	−0.03	0.08	−0.33	.74
Pos 1, 2, & 3 vs. Pos 4 × Presentation Direction	0.00	0.08	−0.00	.99
Pos 1, 2, 3, & 4 vs. Pos 5 × Presentation Direction	0.16	0.07	2.14	<.05
Pos 1, 2, 3, 4, & 5 vs. Pos 6 × Presentation Direction	0.28	0.07	3.72	<.001

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 were 1.4 times greater with congruent presentation, as 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 the error 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 were 1.6 times greater with incongruent presentation, as 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, note the increase in these errors in the middle of the list, which is 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, more reflections occurred with incongruent presentation at all serial positions.

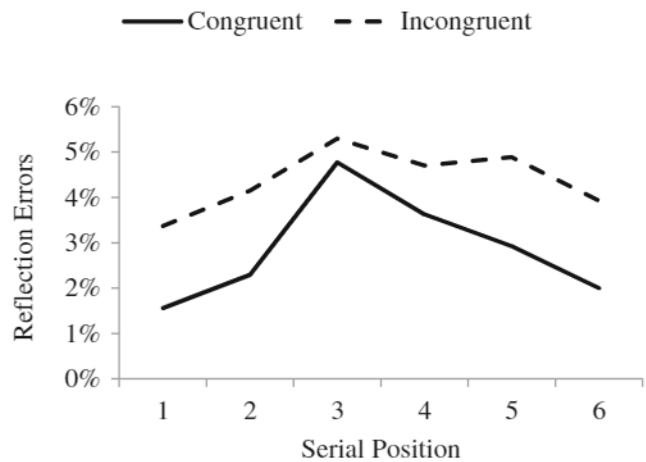

Fig. 2 Reflections as a function of serial position for Experiment 1, with congruent (solid line) and incongruent (dashed line) presentation directions

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 locations of items on the screen affects the 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 was 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 was 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 that 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 toward 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 backward recall. Although encoding and maintenance are argued to be shared between forward and backward recall, the two tasks have been argued to differ in retrieval processes, with backward recall potentially relying more on visuospatial cues (Li & Lewandowsky, 1995). Comparing the

Table 3 Error rates 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 %
	Odds Ratio	1.1	1.6	1.0
Experiment 2	Congruent	7.5 %	3.4 %	7.5 %
	Incongruent	7.9 %	4.6 %	8.6 %
	Odds Ratio	1.1	1.4	1.2
Experiment 3	Congruent	10.5 %	2.8 %	9.8 %
	Incongruent	11.6 %	9.2 %	10.1 %
	Odds Ratio	1.1	3.5	1.0

effects of presentation direction across these tasks will help localize the cognitive mechanism responsible for this effect.

Experiment 2

Method

Participants A group of 60 students (33 female, 27 male) 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 The deign and procedures were identical to those of Experiment 1, except that participants were instructed to recall the letters in the reverse temporal order from the one 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 incongruent lists). Figure 3 plots serial position curves by presentation directions. 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 being 1.2 times greater in the congruent condition. The interaction between presentation direction and serial position was significant, with a larger effect at Position 6 than at Positions 1–5. None of the other interactions were significant.

Table 4 Fixed-effect estimates for the multilevel logit model of recall accuracy in Experiment 2

Fixed Effect	Coefficient	*SE*	Wald *z*	*p*
(Intercept)	1.72	0.17	10.09	<.001
Presentation Direction	−0.22	0.09	−2.45	<.05
Pos 1 vs. Pos 2	−0.17	0.02	−5.08	<.001
Pos 1 & 2 vs. Pos 3	−0.05	0.03	−1.33	.18
Pos 1, 2, & 3 vs. Pos 4	0.19	0.03	4.06	<.001
Pos 1, 2, 3, & 4 vs. Pos 5	0.67	0.04	15.10	<.001
Pos 1, 2, 3, 4, & 5 vs. Pos 6	1.24	0.05	19.47	<.001
Pos 1 vs. Pos 2 × Presentation Direction	0.02	0.05	0.37	.71
Pos 1 & 2 vs. Pos 3 × Presentation Direction	0.11	0.06	1.74	.08
Pos 1, 2, & 3 vs. Pos 4 × Presentation Direction	0.02	0.06	0.26	.80
Pos 1, 2, 3, & 4 vs. Pos 5 × Presentation Direction	−0.02	0.08	−0.15	.88
Pos 1, 2, 3, 4, & 5 vs. Pos 6 × Presentation Direction	−0.28	0.10	−2.59	<.05

Table 3 displays the distribution of error types. As in Experiment 1, reflections were the least common error type (4.0 %; vs. intrusions [7.7 %] and other transpositions [8.1 %]). Yet, whereas 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.

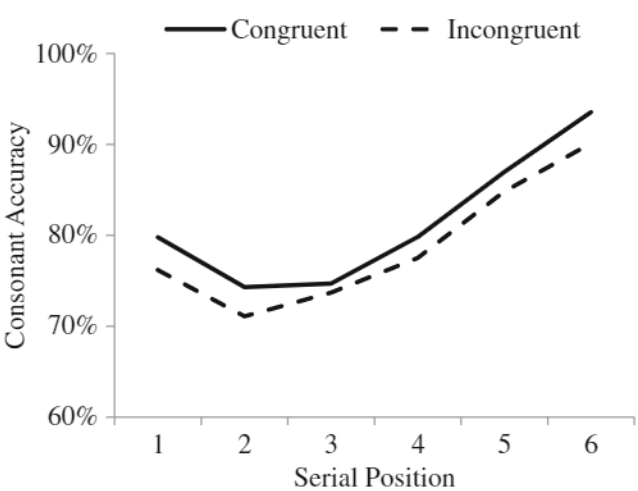

Fig. 3 Serial-position curves for Experiment 2, for backward serial recall of lists with congruent (solid line) and incongruent (dashed line) presentation directions. Note that position reflects the input rather than the output position

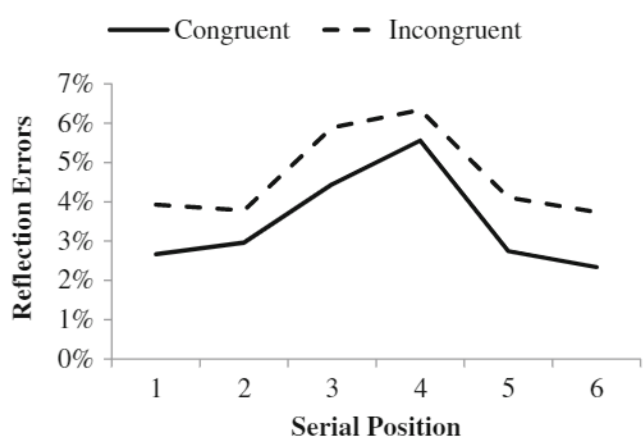

Fig. 4 Reflections as a function of serial position for Experiment 2, with congruent (solid line) and incongruent (dashed line) presentation directions

Discussion

As with forward recall, the odds of correctly recalling an item in backward recall was greater with congruent than with incongruent presentation. Although the main effect of presentation direction was significant in Experiment 2, but not in Experiment 1, the odds of correct recall were equivalently affected (1.2 times greater) by congruent presentation in both experiments, suggesting that the effect is not modulated by recall direction. Again, a disproportionately large increase was found in reflections across all serial positions with incongruent presentation, as is 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 A group of 60 students (39 female, 21 male) 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 The design and procedures were identical to those in Experiments 1 and 2, with several key exceptions. First, participants saw eight 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 congruent and 69.1 % with incongruent presentation). Figure 5 plots serial-position curves by presentation and recall directions. For this experiment, the log odds of

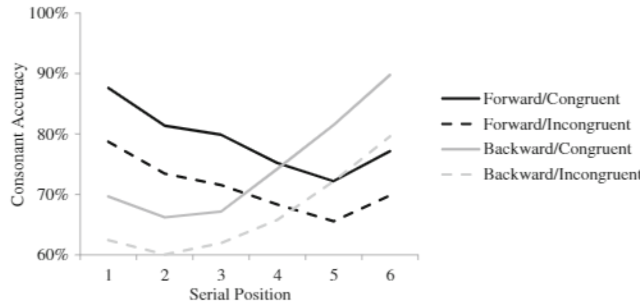

Fig. 5 Serial-position curves for Experiment 3, for both forward (black lines) and backward (gray lines) serial recall of lists with congruent (solid lines) and incongruent (dashed lines) presentation directions. For backward recall, position reflects the input rather than the output position

correct item recall were predicted by serial position, presentation and recall directions, 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 the parameter estimates for the full model. Recall direction had a clear effect on accuracy, with the odds of recall being 1.2 times greater for forward recall. Presentation direction also had a clear effect on accuracy, with the odds of recall being 1.5 times greater in the congruent condition. None of the three-way interactions were significant, except for the interaction between presentation direction, recall direction, and the final versus the first five positions in the serial-position function.

Table 3 shows the distribution of errors for congruent and incongruent presentation, collapsed across recall directions. Intrusions were the most frequent error type (11.1 %), followed by other transpositions (10.0 %), with reflections being the least common type (6.0 %). However, the odds of producing a reflection error were 3.5 times greater in the incongruent condition, whereas the increases in the odds of producing intrusions (1.1) and other transposition errors (1.0) were much less substantial. Figure 6 plots reflections by serial position and list type. The increase in reflections can be observed at all serial positions.

Discussion

As in the two previous experiments, the odds of correctly recalling an item were greater for congruent lists. Furthermore, when rehearsal strategies were disrupted by postcuing recall direction, the effect was larger for both forward and backward recall, and the interaction with serial position was reduced. This large effect again was primarily driven by a large increase in the number of reflections, as

Table 5 Fixed-effect estimates for the multilevel logit model of recall accuracy in Experiment 3

Fixed Effect	Coeff	*SE*	Wald *z*	*p*
(Intercept)	1.26	0.17	7.63	<.001
Presentation Direction	0.48	0.15	3.17	<.01
Recall Direction	0.28	0.08	3.59	<.001
Presentation Direction × Recall Direction	−0.03	0.09	−0.35	.72
Pos 1 vs. Pos 2	−0.19	0.03	−5.72	<.001
Pos 1 & 2 vs. Pos 3	−0.13	0.04	−3.04	<.01
Pos 1, 2, & 3 vs. Pos 4	−0.09	0.04	−2.17	<.05
Pos 1, 2, 3, & 4 vs. Pos 5	0.02	0.05	0.49	.62
Pos 1, 2, 3, 4, & 5 vs. Pos 6	0.42	0.05	7.95	<.001
Pos 1 vs. Pos 2 × Presentation Direction	−0.03	0.05	−0.56	.58
Pos 1 & 2 vs. Pos 3 × Presentation Direction	−0.02	0.05	−0.40	.69
Pos 1, 2 & 3 vs. Pos 4 × Presentation Direction	0.02	0.05	0.35	.72
Pos 1, 2, 3, & 4 vs. Pos 5 × Presentation Direction	0.02	0.06	0.39	.70
Pos 1, 2, 3, 4, & 5 vs. Pos 6 × Presentation Direction	0.10	0.06	1.58	.11
Pos 1 vs. Pos 2 × Recall Direction	−0.18	0.05	−4.00	<.001
Pos 1 & 2 vs. Pos 3 × Recall Direction	−0.27	0.05	−5.29	<.001
Pos 1, 2, & 3 vs. Pos 4 × Recall Direction	−0.66	0.05	−12.29	<.001
Pos 1, 2, 3, & 4 vs. Pos 5 × Recall Direction	−1.07	0.06	−19.11	<.001
Pos 1, 2, 3, 4, & 5 vs. Pos 6 × Recall Direction	−1.22	0.06	−19.11	<.001
Pos 1 vs. Pos 2 × Recall Direction × Presentation Direction	0.01	0.09	0.07	.94
Pos 1 & 2 vs. Pos 3 × Recall Direction × Presentation Direction	0.05	0.10	0.42	.67
Pos 1, 2, & 3 vs. Pos 4 × Recall Direction × Presentation Direction	−0.14	0.11	−1.30	.19
Pos 1, 2, 3, & 4 vs. Pos 5 × Recall Direction × Presentation Direction	−0.17	0.11	−1.49	.14
Pos 1, 2, 3, 4, & 5 vs. Pos 6 × Recall Direction × Presentation Direction	−0.25	0.13	−1.98	<.05

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 (Exp. 1 vs. Exp. 2), and was more pronounced when participants could not anticipate the recall direction during encoding (Exp. 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, with the item being recalled in a position far from its correct position in some errors (e.g., recalling the first item last) and the item being recalled in a position adjacent to its correct position in others (e.g., recalling the third item fourth). In short, the three experiments demonstrate a replicable effect of spatial and temporal order congruence in ISR.

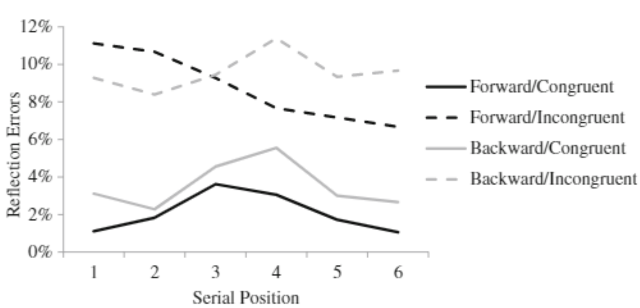

Fig. 6 Reflections as a function of serial position for Experiment 3, for both forward (black lines) and backward (gray lines) recall with congruent (solid lines) and incongruent (dashed lines) presentation directions

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 being closer to the beginning of the sequence, as are items that appear farther 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 does incongruent spatial information. Figure 7 depicts the sequence of the letters ABC with both congruent and incongruent presentation directions, as well as the order representations of these two different presentations. Because the A in the congruent presentation appears as both the leftmost 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, since 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 error data.

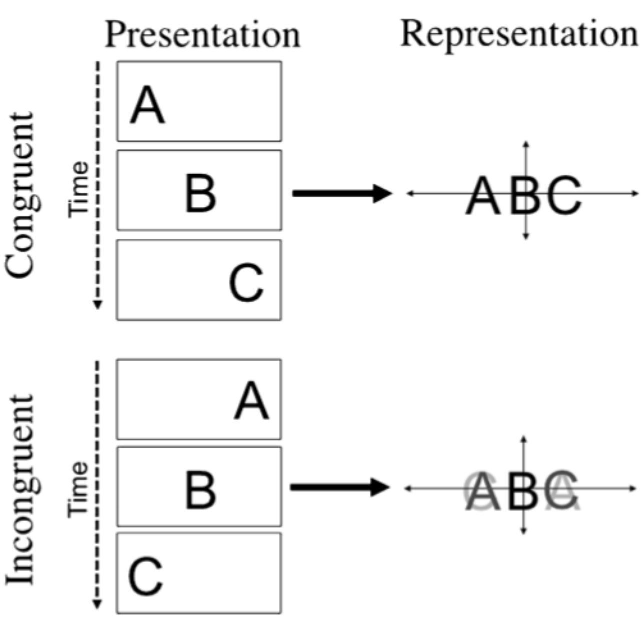

Fig. 7 Depiction of representations of the order of letters for the temporal letter sequence ABC, with congruent and incongruent spatial presentation directions

Although spatial–temporal congruence effects were observed in all three experiments, the sizes 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 sizes 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 postcuing recall direction disrupts subvocal rehearsal strategies (e.g., Hinrichs, 1968). The subvocal rehearsal strategy used in Experiments 1 and 2 masked 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 postcuing recall direction (Exp. 3), a larger spatial–temporal order congruence effect is observed across the entire list.

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

Author note This research was supported by a research fellowship from the Beckman Foundation to S.F.-B. Thanks to Maureen Gillepsie and Scott Fraundorf for useful suggestions.

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