A Transposed-Word Effect Across Space and Time: Evidence from Chinese

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Abstract

A compelling account of the reading process holds that words must be encoded serially, and so recognized strictly one at a time in the order they are encountered. However, this view has been challenged recently, based on evidence showing that readers sometimes fail to notice when adjacent words appear in ungrammatical order. This is argued to show that words are actually encoded in parallel, so that multiple words are processed simultaneously and therefore might be recognized out of order. We tested this account in an experiment in Chinese with 112 skilled readers, employing methods used previously to demonstrate flexible word order processing, and display techniques that allowed or disallowed the parallel encoding of words. The results provided evidence for flexible word order processing even when words must be encoded serially. Accordingly, while word order can be processed flexibly during reading, this need not entail that words are encoded in parallel.

Keywords: word-transposition effect, serial processing, parallel processing, reading.

1. Introduction

An ongoing controversy in reading research concerns whether words are recognized strictly serially, one at a time in reading, or else encoded in parallel so that multiple words might be processed simultaneously. Serial processing accounts, exemplified by the E-Z Reader model (Reichle et al., 1998, 2003), require that attention is allocated to one word at a time, and that words are recognized in the order they are encountered. By comparison, parallel processing models, such as SWIFT (Engbert et al., 2005), Glenmore (Reilly & Radach, 2006) and, most recently, OB1-Reader (Snell et al., 2018), are based on the alternative assumption that words are encoded in parallel, within a narrow spatial region around the location the reader currently is fixating. It further is assumed that attention is graded across this region, so that greater attention is allocated to words that are closer to fixation, thereby constraining the order in which words might be recognized.

Advocates of serial accounts nevertheless argue that parallel encoding is implausible as it would limit the system's ability to keep track of word order, and might lead to words being recognized out of order (Reichle et al., 2009; White et al., 2019). However, supporters of parallel processing contend that such problems are inherent to reading (Snell & Grainger, 2019a), based on experiments that used a grammatical decision task to show that readers can misprocess word order (Mirault et al., 2018; Snell & Grainger, 2019b; see also Kennedy & Pynte, 2008). The focus of these experiments was on short sentences in which two adjacent words were transposed. Base forms of the sentences were either grammatical (e.g., "The white cat was big" became "The white was cat big") or ungrammatical (e.g., "The white cat was slowly" became "The white was cat slowly"), and transposing words always produced ungrammatical sentences. Participants made grammatical decisions for these stimuli and for an equal number of grammatically correct sentences of similar construction. The key finding was that participants made more errors and slower correct responses for transposed-word stimuli derived from grammatical than ungrammatical base sentences. This was argued to demonstrate that flexible word order processing allowed participants to access a representation of the base grammatical sentences (i.e., with the correct word order), interfering with their decisions to correctly categorize stimuli as ungrammatical. Essentially the same effects were observed in subsequent experiments employing these methods in Chinese, demonstrating that the transposed-word effect can be replicated cross-linguistically using a non-alphabetic orthography (Liu et al., 2020, 2021).

This effect is explained within a parallel processing architecture, such as OB1-Reader, in terms of noisy (i.e., uncertain) word position encoding (Snell & Grainger, 2019a,b). Within this model, multiple words are recognized in parallel, then mapped onto a spatiotopic representation of sentence structure in short-term memory. This mapping is imprecise, however, as multiple words can be active in parallel and the system may have difficulty keeping track of their order. The model therefore allows for visual cues to word length and top-down syntactic and contextual knowledge to guide the mapping process. These constraints can lead to words being processed out of the order they appear in the text, especially if this supports a plausible interpretation of the input. Other explanations are possible, however, in which words are processed serially, in the order they appear in text, and are re-ordered subsequently. For example, “noisy channel” models of sentence processing incorporate the assumption that perceptual input is typically imperfect, and that the syntactic processor can edit or reorder elements of the input to achieve a plausible interpretation of its meaning (Gibson et al., 2013). Such models are agnostic as to whether input is obtained via serial or parallel encoding. Consequently, while it is argued that parallel encoding provides a natural mechanism for flexible word order processing (Snell & Grainger, 2019a), this could be achieved within a model in which perceptual input is obtained serially. This raises the question of whether parallel encoding is necessary to produce the transposed-word effect.

We tested this experimentally, using methods adapted from previous research. We conducted our experiment in Chinese, employing stimuli used by Liu et al. (2020). As in previous research, participants made grammatical decisions for transposed-word stimuli derived from grammatical and ungrammatical base sentences. To allow parallel encoding, half the stimuli were presented using the same display format as previous research, so that sentences were viewed normally, as a horizontal sequence of words (i.e., using parallel visual presentation, PVP, displays). The other half were presented using serial visual presentation (SVP) displays in which sentences were presented one word at a time, at a fixed rate, at the screen center. This ensured that words were encoded serially. The crucial question was whether a transposed-word effect, characterized by increased errors and slower correct responses for stimuli derived from grammatical than ungrammatical base sentences, would be restricted to displays allowing for parallel encoding or also observed when serial encoding is obligatory.

Whether a transposed-word effect might occur with the same probability in the two displays is less clear, as other differences in how stimuli are presented might also influence performance. For example, stimuli in PVP displays are shown as standard Chinese sentences, which are naturally unspaced and lack visual cues to word boundaries so that readers must cognitively segment the text into words (e.g., Li et al., 2015). By comparison, word boundaries are explicitly demarcated by the word-by-word presentation method used in SVP displays. How this will affect performance is unclear, but it might lead to differences in the perception of the grammaticality of stimuli regardless of experimental condition, and so affect the probability of noticing a word transposition. We will return to this issue, and the potential for display characteristics to introduce differential response biases, when considering our results.

2. Method

The study was approved by the research ethics committee in the Academy of Psychology and Behavior at Tianjin Normal University and conducted in accordance with the principles of the Declaration of Helsinki.

2.1 Participants.

Participants were 112 undergraduate students, aged 18-24 years (*M* = 20 years) from Tianjin Normal University. All were native Chinese readers with normal or corrected vision and paid 30 yuan for their participation. Sample size decisions were guided by the Liu et al. (2020) study, which produced word-transposition effects using the same stimulus sets (described below) in experiments with sample sizes of 63 and 69 respectively.

2.2 Stimuli & Design.

Two stimulus sets were used, each containing 160 five-word sentences from Liu et al. (2020), created following procedures described by Mirault et al. (2018). Each set comprised 40 experimental items created by transposing the third and fourth words in grammatical base sentences, and 40 control items created by transposing the same words in ungrammatical base sentences. In one set, an adjacent pair of one-character words was transposed; in the other, an adjacent pair of two-character words was transposed. In each set, these transposed-word stimuli were combined with another 80 grammatically correct sentences of the same length and of similar construction. Figure 1 shows an example from each stimulus set, illustrating how experimental and control transposed-word stimuli were created from matched pairs of grammatical and ungrammatical base sentences that differed only in their final words.

Figure 2 illustrates the sequence of events in PVP and SVP displays. In PVP displays, each trial began with a fixation cross presented at a central screen location, followed by the presentation of a stimulus shown normally, as a horizontal series of characters. In SVP displays, each trial began with a fixation cross presented at a central screen location. This was followed by the presentation of a stimulus one word at a time, at a fixed rate (250 ms per word), at the same central screen location. Half the participants viewed the one-character stimuli in PVP displays, and the two-character stimuli in SVP displays, with this allocation reversed for the other participants. Trials using each display type were presented in separate blocks. Block order was counterbalanced across participants so that half the participants viewed PVP trials first, followed by SVP trials, with the order reversed for the other participants. To be clear, each participant viewed one-character stimuli in PVP displays and two-character stimuli in SVP displays or vice versa. Both sets of words had been shown previously to produce similar transposed-word effects in error rates in a grammatical decision task using PVP displays (Liu et al., 2020). Consequently, as the allocation of stimulus sets to PVP and SVP displays and the order these displays were presented was counterbalanced across participants, it seemed unlikely that this approach would create a confound.

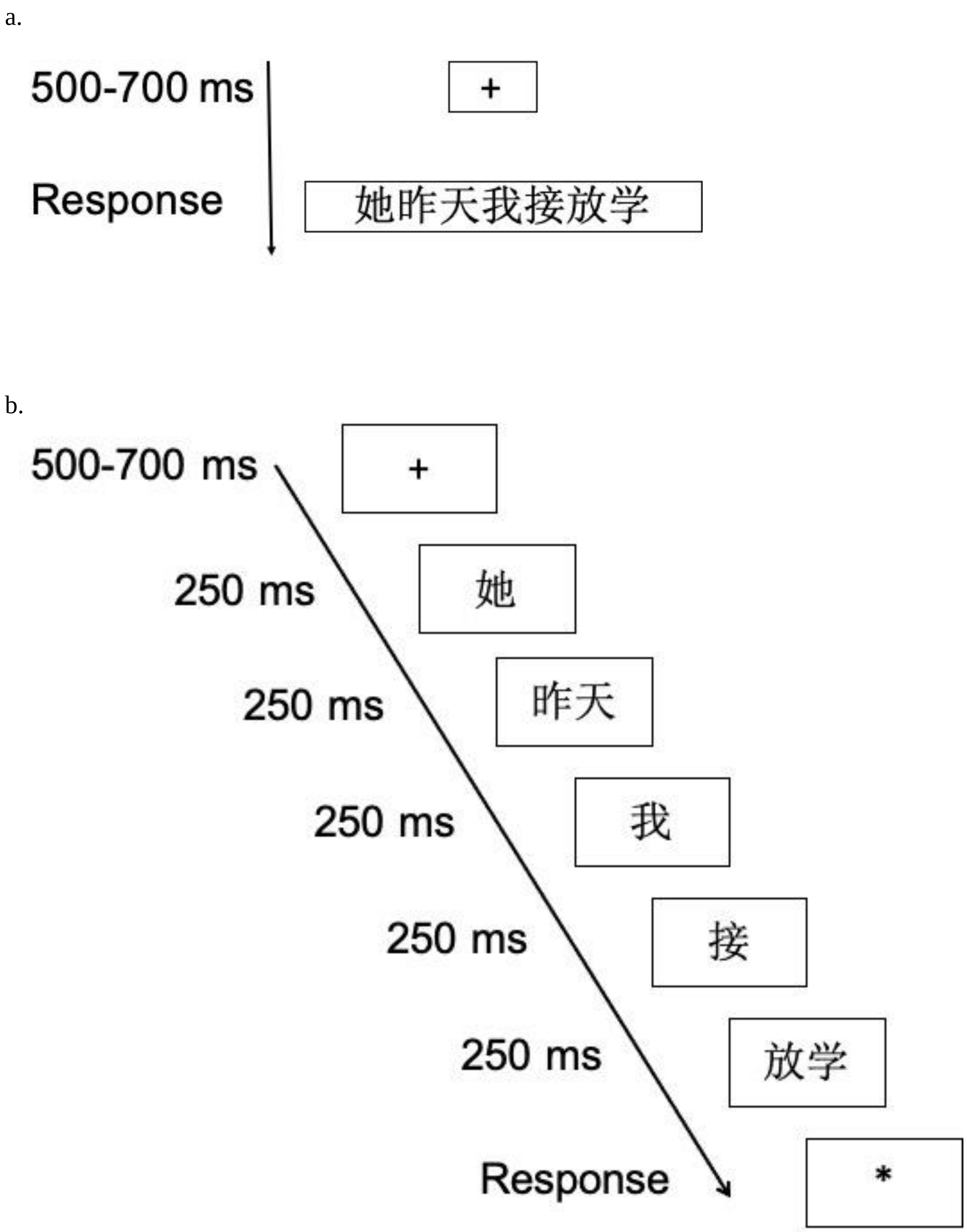
Accordingly, the experiment manipulated display type (PVP, SVP), stimulus type (experimental, control), and transposed-word length (one-character, two-character) using a within-participants design. We examined the effects of these variables on error rates and the latency of correct responses in a grammatical decision task.

Figure 1. Examples of Construction of Transposed-Word Stimuli Derived from Grammatical and Ungrammatical Base Sentences.

Base Sentences		Transposed-Word Stimuli		Transposed-Word Stimuli in English
One-Character Transposed Words				
Grammatical	她昨天**接我**放学	Experimental	她昨天**我接**放学	Yesterday she me pick up after school.
	她就是**不听**劝告		她就是**听不**劝告	She just listen to didn’t the advice.
Ungrammatical	她昨天**接我**劝告	Control	她昨天**我接**劝告	Yesterday she me pick up the advice.
	她就是**不听**放学		她就是**听不**放学	She just listen to didn’t after school.
Two-Character Transposed Words				
Grammatical	他的**公司生产**鞋	Experimental	他的**生产公司**鞋	His produces company shoes.
	她的**笑容非常**美		她的**非常笑容**美	Her is very smile beautiful.
Ungrammatical	他的**公司生产**美	Control	他的**生产公司**美	His produces company beautiful.
	她的**笑容非常**鞋		她的**非常笑容**鞋	Her is very smile shoes.

The figure shows examples of the grammatical and ungrammatical base sentences and the corresponding transposed-word stimuli created for stimulus sets containing either one- or two-character transposed words. Grammatical and ungrammatical base sentence pairs differed only by the interchange of sentence-final words. Transposed-word stimuli were created by reversing the order of the third and fourth words in the base sentences, so that experimental items were derived from grammatical base sentences and control items were derived from ungrammatical base sentences. Note that only the transposed-word stimuli, not the base sentences, were used in the experiment, intermixed with an equal number of other grammatically correct stimuli. Transposed words are shown in bold but these were shown as normal in the experiment.

Figure 2. Example of (a) parallel visual presentation (PVP) and (b) serial visual presentation (SVP) displays.



2.3 Apparatus & Procedure.

Stimuli were presented using E-Prime (Version 2.0.10; Psychology Software Tools, Pittsburgh, PA) and displayed on a 14-inch LCD screen in 30-point Song font as black text on a white background. At 55 cm viewing distance, each character subtended approximately 1° and so was of normal size for reading. Responses were recorded via the computer's keyboard, using "F" and "J" keys for grammatical and ungrammatical decisions respectively.

The procedure was explained to participants at the start of the experiment. Participants placed the index and middle finger of their dominant hand over the "F" and "J" keys. They were instructed to use these keys to indicate, as quickly and as accurately as possible, whether each stimulus was grammatically correct. Each trial began with a central fixation cross, presented for a random duration between 500 and 700 ms (following Mirault et al., 2018). This was replaced by a stimulus display. For PVP displays, each stimulus was shown normally as an unspaced horizontal sequence of characters, at screen center, and terminated by a keypress response or timed out after 3000 ms. For SVP displays, each stimulus was presented one word at a time, at a fixed rate (250 ms per word), centered at the fixation cross, and terminating with a cue for participants to respond. Accordingly, while PVP displays were visible until a response was made (or timed out), SVP displays were presented for a fixed period (250 ms per word) prior to response. Stimuli presentation order was randomised in each block. The experiment lasted about 30 minutes per participant.

3. Results

Response accuracy and the latency of correct responses are shown in Table 1 and statistical effects summarized in Table 2. Figure 2 illustrates the effects graphically. Average response accuracy was high across display types (PVP, *M* = 88.6%, *SD* = 6.4%; SVP, *M* = 94.5%, *SD* = 3.3%). Following log-transformation, trials with response times more than 2.5 SD from each participant's grand mean were removed (affecting 1.8% of trials for PVP displays and 2.9% of trials for SVP displays).

Data for the transposed-word stimuli were analysed using the lme4 package (Bates et al., 2015) in R (R Development Core Team, 2016). Errors were analysed using a generalized linear mixed-effects model, and correct response latencies were analysed using a linear mixed-effects model, with display type (PVP, SVP), stimulus type (experimental, control), and transposed-word length (one-character, two-character) – as well as interactions between these variables –as fixed factors. Fixed factors were coded as .5 for one level and -.5 for the other. Participants and stimuli were treated as random effects. We attempted to use a maximal random structure (Barr et al., 2013), though some slopes were removed because of convergence issues. Results for log-transformed response latencies are reported although untransformed analyses produced the same effects. We show untransformed means in Table 1 and Figure 2 for transparency. Following convention, *t/z* values > 1.96 were considered statistically significant.

Table 1. Mean Error Rates and Latencies for Correct Responses (RT) in PVP and SVP Tasks

Stimulus Type	Transposed Word Length	PVP		SVP	
		Errors (%)	RT (ms)	Errors (%)	RT (ms)
Grammatical		3.5 (.2)	1119 (4)	3.3 (.2)	436 (3)
Experimental	One-Character	33.3 (1)	1398 (11)	9.4 (.6)	524 (7)
	Two-Character	30.1 (1)	1345 (11)	12.9 (.7)	483 (7)
Control	One-Character	8.5 (.6)	1282 (9)	3.3 (.4)	504 (5)
	Two-character	6.0 (.5)	1173 (9)	3.4 (.4)	477 (6)

Note. The Standard Error of the Mean is shown in parentheses.

Table 2. Summary of Statistical Effects

	Errors			RT		
	B	*SE*	*Z*	*B*	*SE*	*t*
Intercept	-2.63	0.09	-28	6.58	0.02	297.01
Display Type	-1.09	0.11	-9.49*	-1.09	0.03	-41.83*
Stimulus Type	1.80	0.11	15.20*	0.05	0.01	3.65*
Word Length	0.10	0.15	0.72	0.08	0.03	2.61*
Display Type x Stimulus Type	-0.89	0.15	-5.77*	-0.13	0.02	-8.24*
Display Type x Word Length	-0.65	0.30	-2.19*	0.02	0.08	0.25
Stimulus Type x Word Length	-0.19	0.30	-0.96	-0.02	0.08	-0.83
Display Type x Stimulus Type x Word Length	0.25	0.31	0.80	0.08	0.04	2.18*

Note. Asterisks indicate statistically significant effects at *t/z* > 1.96, *p* < .05

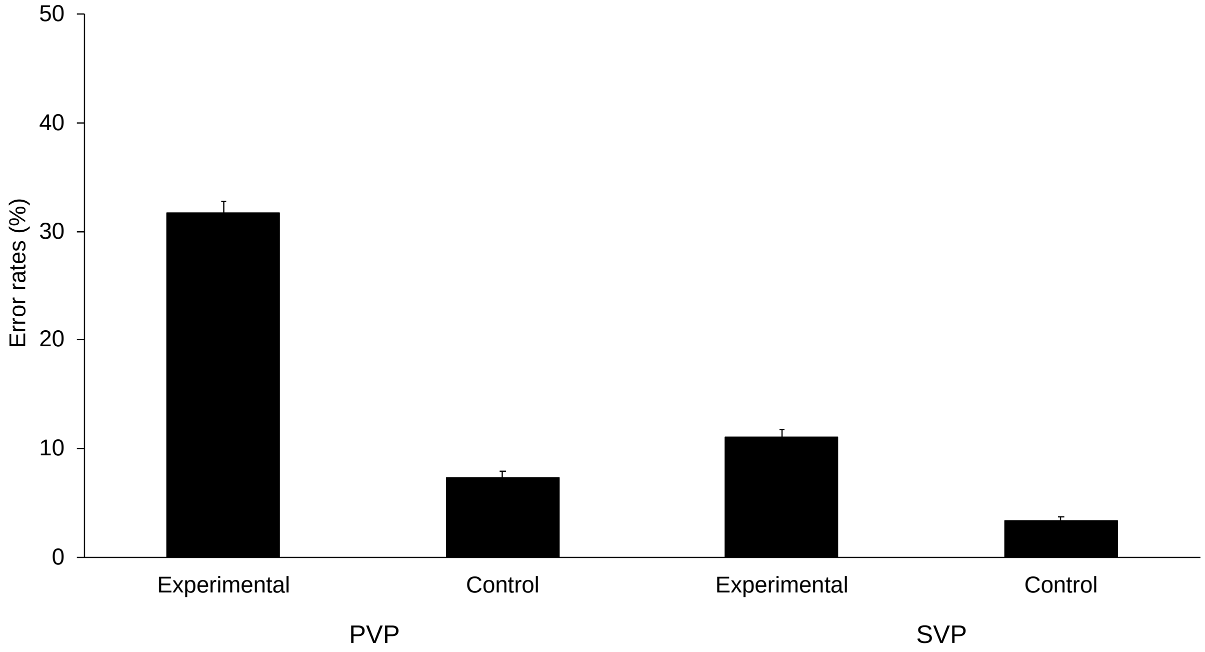
3.1 Error rates

More errors were made for stimuli in PVP than SVP displays. This may be because of a response bias in which there is an overall stronger tendency to judge sentences in PVP displays to be grammatical. We consider this possibility further shortly. A main effect of stimulus type was consistent with a transposed-word effect, with more errors for transposed-word stimuli created from grammatical than ungrammatical base sentences. There was also an interaction between display type and stimulus type. To examine this further, we constructed an additional model, with stimulus type and word length effects nested under the display type effect, to test whether a transposed-word effect was present in both displays. This showed that the transposed-word effect was significant for both PVP ($b = 2.22$, $SE = 0.11$, $z = 21.17$) and SVP ($b = 1.35$, $SE = 0.13$, $z = 10.76$) displays. However, we note that the size of this effect was smaller for SVP than PVP displays (7.8% versus 24.4% effects), which again might reflect a differential response bias in the two display types.

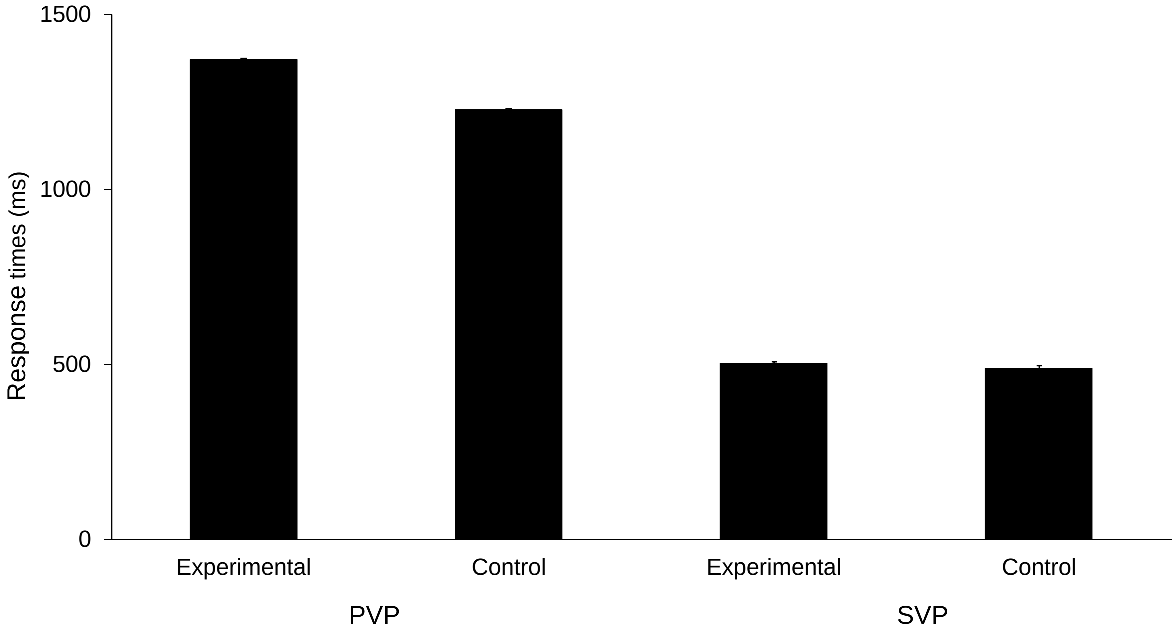
Finally, an interaction between display type and transposed-word length reflected a larger effect of transposed-word length on error rates in PVP displays (2.8% effect) than in SVP displays (a -1.8% effect in the opposite direction). This suggests minor differences in the processing of one-character and two-character words in the different displays. There was no significant three-way interaction in error rates.

Figure 3. Accuracy (a) and Latencies for Correct Responses (b) in PVP and SVP tasks. Error bars show the Standard Error of the Mean.

a.



b.



3.2 Response latencies for correct responses

Main effects of display type and transposed-word length were attributable to differences in task procedure and stimulus characteristics. A main effect of stimulus type, reflecting a transposed-word effect in response latencies due to slower responses for experimental compared to control transposed-word stimuli, was qualified by an interaction with display type. A nested-effects model showed that this effect was observed for PVP displays (b = 0.11, SE = 0.02, t = 7.25), but not SVP displays (b = -0.01, SE = 0.01, t = -0.82). Consequently, while we observed a transposed-word effect in errors for both display types, this transposed-word effect was observed in response latencies only for PVP displays. We consider reasons for this in the Discussion.

3.3 Responses to grammatically correct stimuli

As already noted, a larger transposed-word effect in error rates for PVP versus SVP displays may represent a stronger overall tendency for participants to judge sentences in PVP displays to be grammatically correct regardless of their experimental condition (see Hammerly et al., 2019, for an example of a similar differential response bias in a grammaticality judgment task). To test this, we examined error rates for the grammatically correct stimuli which were included in the experiment to balance the probability of encountering a grammatically correct or incorrect stimulus on each trial. If a differential response bias is present (with a stronger overall tendency to judge PVP displays to be well-formed), we might expect fewer errors for grammatically correct stimuli in PVP than SVP displays. Mean error rates (and mean correct response times) are shown in Table 1. A generalized linear effects model was used to analyze the error data, with task (PVP, SVP) as a fixed effect, and participants and stimuli as crossed random effects. The model revealed no significant effects of task (b = -0.20, SE = 0.21, z = -0.95). Error rates for grammaticality correct stimuli therefore showed no indication of a differential response bias.

4. Discussion

We set out to establish if the transposed-word effect, which occurs when readers misprocess word order in sentences, is restricted to displays in which parallel word encoding is possible or also obtained when words must be encoded serially. To do so, we used the speeded grammatical decision task used to demonstrate this effect previously (e.g., Mirault et al., 2018), and stimuli used to replicate it in Chinese (Liu et al., 2020). Unlike in previous research, stimuli were presented using both PVP displays, which allowed for parallel word encoding, and SVP displays in which words had to be encoded serially.

Consistent with previous research, we observed a transposed-word effect for PVP displays, with more errors and slower correct responses for stimuli created from grammatical than ungrammatical base sentences. This can be explained in terms of flexible word order processing allowing participants access to representations of the base grammatical sentences, thereby interfering with their categorization of transposed-word stimuli. Crucially, a similar effect was observed for SVP displays, although only in errors. Moreover, the error effect was smaller for SVP (7.8%) than PVP (24.4%) displays. Accordingly, although a transposed-word effect was obtained in both cases, it manifested differently for the two displays. We consider likely reasons for this shortly. Before that, we first outline the importance of these findings. Specifically, our results show that readers can make word order errors even when words must be encoded serially (i.e., in SVP displays). We consider this to be problematic for accounts attributing the transposed-word effect to parallel word encoding (Snell & Grainger, 2019b). Our findings suggest parallel word encoding is not required to produce this effect. Therefore, the transposed-word effect should not be taken as evidence for parallel encoding or unambiguous support for models, such as OB1-Reader, that incorporate such mechanisms.

The effect we observed was nevertheless larger in PVP than SVP displays. From a parallel processing perspective, this might be argued to show that the effect is more robust when multiple words are available to be processed simultaneously. Within serial accounts, readers also might benefit from multiple words being available, although this benefit would be attributed to an effect of parafoveal processing. This is considered an important component of normal reading (Cutter et al., 2015), which serial accounts describe as a shift in attention from the currently fixated word to the next word, prior to the reader making a forward-directed saccade. This attentional shift allows readers to obtain preview information about the next word which can lead to that word being recognized before the next saccade is made. Consequently, this rapid sequential processing of words, which is possible when multiple words are available, might also provide a mechanism by which readers sometimes misanalyze word order (see Rayner et al., 2013). This would be consistent with a framework proposed recently by Huang and Staub (2021a), in which transposed-word effects are attributed to readers not integrating a word (word n) within a sentence representation in memory prior to identifying the following word (word n+1). Our SVP paradigm may provide more time for readers to integrate word n before word n+1 becomes available for processing, which could explain the smaller transposed-word effect for SVP compared to PVP displays in the present experiment.

Clearly, such possibilities require further exploration. However, methodological differences in how displays were implemented might also be important. One issue is that stimulus presentations were longer for PVP displays. This was because word presentations were strictly time-limited in SVP displays, whereas PVP displays were visible until a response was made. A further issue relates to response time recording. For PVP displays, this began from stimulus onset but, for SVP displays was initiated following the final word in each stimulus. This difference was unavoidable but meant that response times captured both stimulus encoding and response selection for PVP displays, but primarily response selection for SVP displays. Finally, whereas text was naturally unspaced in PVP displays, word boundaries were unambiguous in SVP displays. Crucially, how stimuli were presented in the two displays may have created differential biases whereby there was a stronger tendency for participants to judge sentences in PVP displays to be grammatical. We tested this possibility by examining error rates for the grammaticality correct stimuli in the experiment. These error rates might be expected to be lower for PVP than SVP displays if such a bias exists. We observed no such difference in error rates, and so no evidence for a differential response bias. This is not to say that such a bias does not exist, however, and this issue would benefit from further investigation, including using methods from signal detection theory to systematically test for response bias (see, e.g., Hammerly et al., 2019).

Given these issues, it is important to note resonance between the present findings and research on serial memory recall (for a review, see Hurlstone et al., 2014). This research concerns the encoding and recall of ordered sequences from short-term memory. Some studies use both sentences and unstructured word sequences as stimuli (Allen et al., 2018), which are presented to participants serially, one word at a time (using aural and visual presentations). Immediately following each stimulus presentation, participants compare this against a test sequence, also presented serially. The test sequence is either identical to the stimulus or changed by transposing two words, with both word orders being grammatical when sentences are used as stimuli. Of particular relevance is the finding that participants often misjudge stimulus and test sequences to be the same when adjacent words are transposed, with few such errors when transposed words are farther apart in the sequence (and see Snell & Grainger, 2019a, for a similar limitation to the transposed-word effect). As with the transposed-word effect, this is taken as evidence for positional uncertainty in the representation of information in short-term memory. Moreover, as in the present experiment, the effect is observed when words are encoded serially. Consequently, while it remains to be determined if the two approaches tap the same memory processes, evidence from both suggests that parallel encoding is not required to produce word order errors.

Accordingly, while the transposed-word effect can be explained by parallel models, such as OB1-Reader (Snell & Grainger, 2019b), it may be compatible with serial models, especially if a level of post-perceptual word order flexibility is assumed, perhaps in line with “noisy channel” accounts of sentence processing (Gibson et al., 2013; for detailed discussion, see Huang & Staub, 2021a). The present research shows that, although readers sometimes misprocess word order, this need not entail that words are encoded in parallel. However, further investigation is required, using methods such as eye movement measures (e.g., Huang & Staub, 2020, 2021b) to uncover how word order is processed online in reading.

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Supplementary Material

Data files and related resources are available from the University of Leicester online Figshare repository: https://figshare.com/s/2284ba0b29b63607bf19 <temporary link: permanent link to follow publication>

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