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Brief article

Parallel, cascaded, interactive processing of words during sentence reading

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ABSTRACT

Single words are easier to identify in a briefly presented syntactically correct word sequence compared with a scrambled version of the same set of words: a sentence superiority effect. Interactive-activation models of sentence comprehension can account for this phenomenon by implementing parallel processing of word identities. The cascaded and interactive nature of such processing allows sentence-level structures to influence ongoing word processing. Alternatively, prior observations of a sentence superiority effect in post-cued word-in-phrase identification might be due to the sophisticated guessing of word identities on the basis of partial information about the target word and the surrounding context. Here, for the first time, we used electrophysiological recordings to plot the time-course of the sentence superiority effect. According to an interactive-activation account of this phenomenon, the effect should be visible in the N400 component, thought to reflect the mapping of word identities onto higher-level semantic and syntactic representations. Such evidence for changes in highly automatized linguistic processing is not predicted by a sophisticated guessing account. Our results revealed a robust and widespread sentence-superiority effect on the N400 component that onsets around 270 ms post-sentence onset, thus lending support to the interactive-activation account.

1. Introduction

How do skilled readers read? This question has been of central interest to experimental psychologists ever since the pioneering work of James McKeen Cattell more than 130 years ago. Cattell is well known for the "word superiority effect" that he established, but it is less well known that Cattell also discovered a "sentence superiority effect". Cattell (1886; reported in Scheerer, 1981) found that sentences consisting of seven words could be recalled correctly after a single brief exposure, whereas only three to four words could be recalled if sequences of words were unrelated. Given that current theories of reading predominantly adopt a one-word-at-a-time incremental processing approach (see Reichle, Liversedge, Pollatsek, & Rayner, 2009, for a review), Snell and Grainger (2017) asked whether Cattell's sentence superiority effect could be taken as evidence against such theories, and on the contrary provide support for theories that appeal to rapid parallel processing of syntactic and semantic information across multiple words during sentence reading (Snell, Declerck, & Grainger, 2018; Snell, Meeter, & Grainger, 2017). Snell and Grainger noted that the methodology used in Cattell's experiments left open possible roles for extra-linguistic factors such as short-term memory and guessing, and therefore, following the methodological innovation offered by Reicher (1969) and Wheeler (1970) in order to counter similar explanations of the word superiority effect, they set-out to study the sentence superiority effect using a post-cued partial report procedure combined with the rapid parallel visual presentation (RPVP) of word sequences (see Fig. 1).[1]

Snell and Grainger (2017) found that word identification was more accurate in grammatically correct normal word sequences than in ungrammatical scrambled sequences. Crucially, this sentence superiority effect was obtained in conditions that minimized any potential influence of between-word semantic relatedness or predictability, as determined by cloze probability measures, thus pointing to syntactic representations as the source of the effect. Additionally, the effect was equal in size across target positions, hence speaking against a serial left-to-right processing approach, which would have predicted stronger effects for right- than leftward target positions, given that ongoing processing of targets at later positions may be constrained by the

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[1] We note here that the sentence superiority effect has also been studied as a memory phenomenon whereby it is easier to recall a list of words that form a syntactically correct sequence compared with an unstructured list of the same words (e.g., Baddeley, Hitch, & Allen, 2009; Bonhage et al., 2017; Jones & Farrell, 2018; Miller & Isard, 1964). The post-cued partial-report RPVP procedure used by Snell and Grainger (2017) and in the present study was expressly designed to limit the role of memory factors. Nevertheless, the 500 ms delay between stimulus offset and cue onset that was implemented in the present study (see Fig. 1) in order to reduce contamination of the EEG signal by preparatory hand movements, could have allowed memory factors to intervene. We address this issue in the Discussion.

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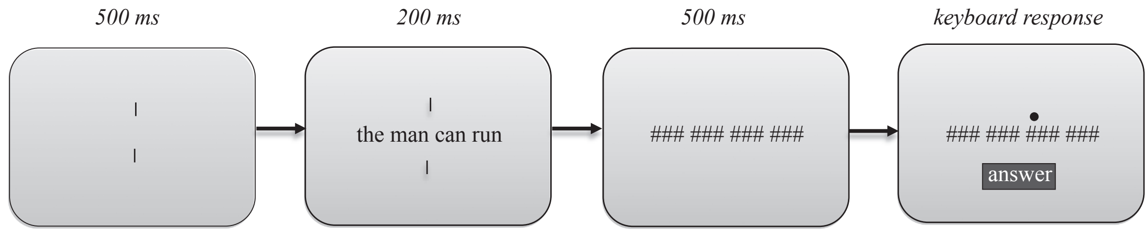

Fig. 1. Illustration of the sequence of events in the post-cued partial report Rapid Parallel Visual Presentation (RPVP) procedure. In the example here, the target word ("can") is embedded in a grammatically correct sequence. An example of a corresponding ungrammatical scrambled sequence would be "run the can man" with the target word at the same position.

preceding context while processing of targets at earlier positions cannot be constrained by the upcoming context. These findings taken together, Snell and Grainger argued that the parallel partial identification of multiple words generates an elementary syntactic representation of the word sequence when the sequence is grammatical, and this syntactic representation then constrains on-going identification processes through feedback to word identities. This explanation of the sentence superiority effect appeals to the key principles of interactive-activation (McClelland & Rumelhart, 1981), parallel, cascaded, and interactive processing, that have been applied to sentence comprehension in the work of Rumelhart (1977) and MacDonald, Pearlmutter, and Seidenberg (1994). The explanation also appeals to the rapid generation of a syntactic frame (e.g., Koriat & Greenberg, 1994) that guides on-going lexical processing (Snell et al., 2017).

Here, we seek further evidence in favor of Snell and Grainger (2017) account of the sentence superiority effect. This is motivated by the fact that incremental processing theorists could still argue that participants in the Snell and Grainger study were gleaning partial information about several words simultaneously, without identifying more than one word at a time, and were using that partial information to guess the identity of the target word. Thus, for example, given the sentence "the man can run" and cued to identify the third word, having identified a noun at position 2, and having information that the target is a 3-letter word beginning with "c", participants could search for a 3-letter verb beginning with "c". We refer to this as "sophisticated guessing", borrowing a term used in the debate concerning different possible interpretations of the word superiority effect (e.g., Johnston, 1978).

Sophisticated guessing is a slow inferential process because it involves an explicit evaluation of the available information in order to narrow down the possible candidates. Therefore, in order to exclude this interpretation of the sentence superiority effect, and to unequivocally provide evidence in favor of an interactive-activation explanation, here we measured the time-course of the effect using electrophysiological recordings. If rapidly activated sentence-level structures can influence on-going word identification processes, then we should find evidence for this influence in the N400 ERP component (Kutas & Federmeier, 2011), thought to reflect resonant processing between word identities and higher-level semantic and syntactic information (Grainger & Holcomb, 2009). Such evidence for changes in highly automatized linguistic processing is not predicted by a sophisticated guessing account.

2. Methods

2.1. Participants

Twenty-four participants (16 females; mean age: 21.2 years, SD = 3.0 years) were paid €20 to participate in the experiment. All participants reported to be native French speakers, right-handed, having no history of neurological, psychiatric or language impairment, and having normal or corrected-to-normal vision. One participant was excluded due to excessive artifacts in the EEG data. For 23 participants included in the analyses, the average self-rated language proficiency score was 8.5, SD = 1.0 (10-point scale, 1 = virtually non-existing, 10 = prefect), and the average LexTALE vocabulary score (Brysbaert, 2013) was 89.5, SD = 4.3.

2.2. Materials and design

We adapted 200 word sequences from Snell and Grainger (2017). Each sequence consisted of four words with the average word length of 4.03 letters, SD = 0.82. The average word frequency in Zipf values was 5.66, SD = 1.08 (Ferrand et al., 2010; van Heuven, Mandera, Keuleers, & Brysbaert, 2014). All sequences were grammatically correct and semantically neutral (see Snell & Grainger, 2017, for details). One of the four words in each sequence was used as the target word, and 50 targets were selected from each word position. To construct a scrambled version of every sequence, all words except for the target switched positions so that the scrambled sequences were syntactically incorrect. Examples of the word sequences are presented in Table S1. Two counterbalanced lists were created, and participants were randomly assigned to one of the lists. As such, all word sequences were presented in both conditions (normal and scrambled), but in only one condition per participant. The full list of materials is presented in the Supplementary Materials.

2.3. Procedure

The study was approved by the "Comité de Protection des Personnes SUD-EST IV" (No. 17/051). All participants gave their written informed consent before the experiment started. Participants were seated in a comfortable chair in a dimly-lit shielded testing room. Each participant received a unique pseudo-randomized presentation order of the stimuli, with the same condition (normal vs. scrambled) occurring no more than five times in a row, and the same target position no more than three times in a row. Stimuli were presented on a CRT monitor (1024 × 768 pixels, 75 Hz) controlled by OpenSesame (Mathôt, Schreij, & Theeuwes, 2012). Each trial began with two vertical fixation bars presented for 500 ms at the screen center, and participants were instructed to fixate between the fixation bars. Next, a sequence of four words was presented for 200 ms, followed by a backward mask with hash marks. After 500 ms presentation of the backward mask, a post-cue was presented with a dot above the target location (balanced across the four possible positions), and participants were asked to report the target by typing in their response on a keyboard (see Fig. 1 for an illustration of visual events in the RPVP paradigm). Feedback was then provided with a green (correct) or red (incorrect) dot presented for 500 ms. The inter-trial interval was set at 500 ms. Participants were instructed to minimize blinks, eye-movements, and body movements during the presentation of word sequences. Prior to the experiment, eight practice trials were used to familiarize the participants with the procedure. The experiment lasted approximately two hours.

2.4. EEG recording and preprocessing

The electroencephalogram (EEG) was recorded at a 1024-Hz sample

Table 1
Results of mixed-effects logistic regression analysis.

Random effects		Variance		SD	
Item	Intercept	1.21969		1.1044	
	Scrambled vs. Normal	0.54789		0.7402	
Subject	Intercept	0.80226		0.8957	
	Scrambled vs. Normal	0.05945		0.2438	
Fixed effects		**Estimate**	**SE**	**z value**	***p***
Scrambled vs. Normal		0.8097	0.1102	7.345	< .001

rate with 64 active electrodes (Biosemi ActiveTwo) arranged in the 10/20 system. Two additional electrodes placed close to Pz (CMS and DRL) were used for online referencing (Metting van Rijn, Peper, & Grimbergen, 1990; Schutter, Leitner, Kenemans, & van Honk, 2006). Two external electrodes were placed at left and right mastoids for offline re-referencing. Four external electrodes were placed below and at the outer canthus of each eye to monitor eye movements. The electrode offset was kept below 30 mV.

EEG data were preprocessed using EEGlab (Delorme & Makeig, 2004) and ERPlab (Lopez-Calderon & Luck, 2014). The continuous EEG was re-referenced off-line to the averaged mastoids and filtered with a high-pass filter at 0.1 Hz. EEG data were then segmented in epochs of 900 ms starting 100 ms before the sentence onset, and baseline-corrected. The epochs were low-pass filtered at 30 Hz. Trials with incorrect target word identification were discarded (34.7% of the data). Bad channels were interpolated. Epochs contaminated by drifts and muscle activity were manually dismissed (2.3% of the data), and epochs containing ocular artifacts were automatically rejected (4.7% of the data). A minimum of 30 epochs were required for each condition (Thierry & Wu, 2007).

2.5. Statistical analysis

For the behavioral accuracy data, we conducted mixed-effects logistic regression (Jaeger, 2008) using the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) in R (Core, 2017). Participants and items were included as random effects (Baayen, Davidson, & Bates, 2008), and random slopes were also included in the analysis (Barr, Levy, Scheepers, & Tily, 2013). For the ERP data, the cluster-based random permutation test implemented in FieldTrip (Maris & Oostenveld, 2007; Oostenveld, Fries, Maris, & Schoffelen, 2010) was conducted from 0 ms to 700 ms post-stimulus on all 64 electrodes (see Supplementary Materials for information about this test).

3. Results

3.1. Behavioral results

Consistent with Snell and Grainger (2017), identification accuracy rates were significantly higher for words presented in the normal condition than in the scrambled condition (average identification accuracy rates: 71.0% vs. 59.5% respectively, $z = 7.345$, $p < .001$, see Table 1 and Fig. 2).[2]

Additional analyses were conducted to investigate the impact of target position on the behavioral sentence superiority effect. The results of four separate mixed-effect modelling analyses revealed that identification accuracy was significantly higher for words presented in the normal condition than in the scrambled condition at all positions (position 1: $b = 0.8033$, SE = 0.1850, $z = 4.341$, $p < .001$; position 2: $b = 0.7219$, SE = 0.2914, $z = 2.477$, $p = .0132$; position 3: $b = 1.26943$, SE = 0.20197, $z = 6.285$, $p < .001$; position 4: $b = 0.5125$, SE = 0.1837, $z = 2.790$, $p < .01$). Therefore, the behavioral sentence superiority effect observed here is not driven by stimuli at a specific target position. We also explored possible interactions with presentation condition (normal vs. scrambled) and position. Given the numerically larger effects seen at position 3 (see Fig. 2), this was used as the reference in order to test whether the effects at this position were significantly larger than at the other positions. The interaction was significant at position 2, $b = -0.61220$, SE = 0.26911, $z = -2.275$, $p = .0229$, and position 4, $b = -0.70490$, SE = 0.24750, $z = -2.848$, $p < .01$, and marginally significant at position 1, $b = -0.46395$, SE = 0.23688, $z = -1.959$, $p = .0502$. Further analyses of a potential impact of target position investigated interactions between presentation condition (normal vs. scrambled) and leftward vs. rightward targets in one analysis, and central vs. peripheral targets in another analysis. The only effect to reach marginal significance was the interaction with central vs. peripheral targets, $z = -1.835$, $p = 0.067$ (all other $|z|$s < 1.5, $ps > 0.15$). This reflects the stronger effects observed with central targets, and particularly at position 3, as is clearly visible in Fig. 2.[3]

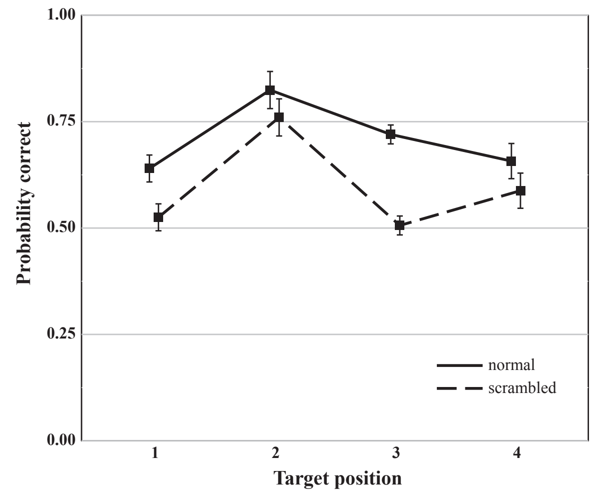

Fig. 2. Mean identification accuracy rates with 95% confidence intervals (Cousineau, 2005) at the four target positions in the normal sentence condition (solid line) and in the scrambled condition (dashed line).

3.2. ERP results

Only trials for which target words were correctly identified were included in the ERP analysis.[4] ERP amplitude was reduced in the normal condition compared to the scrambled condition from 274 to 410 ms (cluster with $p = .018$, see Fig. 3 for results of the permutation test). As can be seen in Fig. 3, the reduced N400 in the normal condition was widely distributed.

4. Discussion

An ERP experiment tested post-cued identification of one word within a sequence of four briefly presented (RPVP) horizontally aligned words. The four words could either represent a grammatically correct

[2] Post-hoc analyses of the behavioral data examined a potential role of type of syntactic structure (dominant vs. non-dominant), and none was found (see Supplementary Materials for details of this analysis).

[3] It should be noted that the frequency and length of targets are similar across target positions (average word frequency in Zipf values at position 1: 5.99, position 2: 4.97, position 3: 5.88, position 4: 4.92; average number of letters at position 1: 3.7, position 2: 4.3, position 3: 4.02, position 4: 4.3).

[4] We also conducted an analysis of the EEG data that included correct and incorrect trials, and the pattern of this overall analysis remained the same.

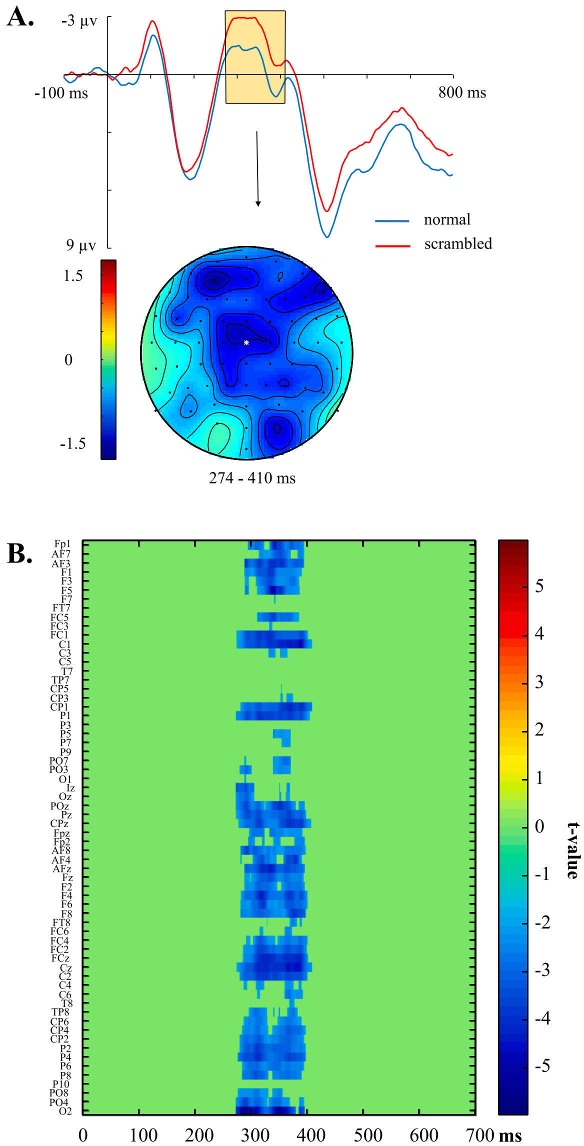

Fig. 3. Results of ERP analyses. (A) ERPs time-locked to the onset of word sequences. Up: ERPs at the Cz electrode; Down: Topography of voltage differences (normal minus scrambled) between 274 and 410 ms with the white star marking the location of the Cz electrode. (B) Results of the permutation test.

sequence (e.g., *she can work now*) or an ungrammatical scrambled sequence of the same words (*now she work can*), and the probability of a correct identification of the same word ("work" in these examples) at the same position was compared across the two contexts. Snell and Grainger (2017) had previously reported that post-cued word identification accuracy was higher when the word was embedded in a syntactically correct sequence compared with an ungrammatical scrambled sequence. They interpreted this finding as reflecting a combination of parallel processing of word identities and the cascaded, interactive nature of processing that connects words with sentence-level structures.

In the present work we recorded electrophysiological activity in order to rule out an alternative sophisticated-guessing account of this sentence superiority effect. The interactive-activation account of the sentence superiority effect predicted that the effect should be seen in the N400 ERP component, a component thought to reflect the interactive processing between word identities and higher-level representations (e.g., Grainger & Holcomb, 2009). That is, rapidly activated sentence-level structures should provide facilitatory feedback to on-going word identification processes when the target word is embedded in a correct sentence. This was expected to reduce N400 amplitude, in line with prior work showing reductions in N400 amplitude by priming single word targets with semantically related primes (e.g., Bentin, McCarthy, & Wood, 1985; Holcomb, 1988) and prior work showing modulation of N400 amplitude as a function of the cloze probability of the target word in a sequence of words (e.g., Freunberger & Roehm, 2017; Lau, Phillips, & Poeppel, 2008; Stites, Payne, & Federmeier, 2017). On the other hand, since the N400 is thought to reflect highly automatized linguistic processing, the slow inferential processes associated with sophisticated-guessing were not expected to modulate N400 amplitude.

The results of the present study are unequivocal. We found a robust widespread influence of sentence structure on the N400, with the effect becoming significant just before 300 ms post-sentence onset. This implies that by this time an initial representation of sentence structure had already been generated on the basis of partial information extracted from several words in parallel, and that sentence-level structures had already began to influence on-going word identification. Furthermore, post-hoc analyses (see Footnote 2 and Supplementary Materials) revealed that the behavioral sentence superiority effect was not driven by a dominant syntactic structure inducing participants to expect certain word categories at certain positions.

Following Snell and Grainger (2017), we interpret the sentence superiority effect as reflecting interactive processing operating between word identities and sentence-level structures. Snell et al. (2017) proposed that during sentence reading, feedback from a sentence-level representation to individual word positions constrains the identification of these words via semantic and syntactic constraints. This is akin to using general sentence-level information to predict word identities, a process that would operate sequentially (incrementally) under standard RSVP presentation conditions, and in parallel under the present RPVP presentation conditions. This is why we predicted an effect on the N400 ERP component and not on syntactic components such as the left anterior negativity (LAN: Friederici, Hahne, & Mecklinger, 1996) or the P600 (Osterhout & Holcomb, 1992). Hagoort (2003) summarizes the ERP evidence for semantic and syntactic effects during sentence comprehension, and the present findings fit well with the theoretical conclusions that were drawn on the basis of this evidence. Hagoort (2003) presents the arguments in favor of an incremental-interactive theory of sentence processing based on Vosse and Kempen (2000) model of sentence parsing (see Hagoort, 2013, for neuro-cognitive extensions of this computational model). The quasi-exclusive use of serial presentation techniques (RSVP) in prior ERP research on written sentence comprehension is the likely reason for the incremental nature of processing that is advocated in this theorizing. In the present work we were able to demonstrate simultaneous processing of multiple words by using the novel RPVP paradigm.

Could our ERP sentence superiority effect be a reflection of differences in working memory load in the normal vs. scrambled conditions? It might have been the case that grammatically correct sequences were more easily retained in memory during the 500 ms interval between stimulus offset and cue onset that was used in the present study. The fact that we observed the same pattern of behavioral effects as the Snell and Grainger (2017) study, where the partial-report cue appeared immediately after stimulus offset, suggests that this is unlikely to be the main factor driving our findings. Furthermore, our N400 sentence superiority effect is clearly distinguishable from the pattern of ERP effects typically observed with visual short-term memory paradigms (e.g., Vogel & Machizawa, 2004). At the same time, it is likely that the sentence superiority effect seen in serial recall does reflect a combination of memory-specific mechanisms (e.g., chunking, redintegration) and linguistic sentence comprehension processes (e.g., Bonhage, Meyer, Gruber, Friederici, & Mueller, 2017; Jones & Farrell, 2018), and it is also clear that sentence comprehension must involve some form of short-term memory, as outlined in our own theoretical work (Snell et al., 2017). Future research could therefore investigate the similarities and differences in the sentence superiority effect observed in memory paradigms and the partial report RPVP paradigm as a means to tease apart the relative contribution of extra-linguistic factors (e.g., memory, attention) and the processing of linguistic information to the observed findings.

Finally, one notable difference with respect to the behavioral results reported by Snell and Grainger (2017) concerns the greater effect of sentence structure at position 3 found in the present work (see Fig. 2). This was supported by analyses revealing significant interactions between the effects of presentation condition at position 3 and the effects observed at both positions 2 and 4. Here we tentatively suggest that small differences in eye fixation location could be the underlying factor. Indeed, there is evidence from eye-tracking studies that people tend to fixate to the right of a central fixation point (Jordan, Patching, & Milner, 1998). Therefore, the numerically larger effect at position 3 might be due to eye fixations tending to be closer to this position than to the other positions, and we note that future research with eye-movement recordings is needed to examine the impact of eye fixation location on the behavioral sentence superiority effect.

In sum, the current results provide evidence in favor of highly interactive processing operating between word-level and sentence-level representations during written sentence comprehension, and more generally for an account of reading that assumes a certain amount of parallel word processing guided by sentence-level constraints (Snell et al., 2017). Of course, given the abundant evidence for serial processing obtained from research recording eye movements during natural reading (see Rayner, 2009, for a review), one could argue that the evidence for parallel processing is due to the specific paradigm that was used (RPVP). This might indeed be the case. However, assuming that no single paradigm is perfect, here we would simply advocate the use of multiple paradigms in reading research, each one providing a different window on the underlying mechanisms. It is by combining these different views that future research can aspire to a greater understanding of how skilled readers derive meaning from text.

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Declarations of interest

None.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2019.04.013.

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