**Segmentation of semantic and perceptual boundaries affects associative memory
and risk of false memories**

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Abstract

Temporally structured sequences of experiences, such as narratives or life events, are segmented in memory into discrete situational models. In segmentation, contextual shifts are processed as situational boundaries that temporally cluster items according to the perceived contexts. As such, segmentation enhances associative binding of items within a situational model. One side effect of enhanced associative processing is increased risk of false recollections for not-presented, semantically related items. If so, do boundaries facilitate false recollections, or does segmentation protect against them? In two experiments, we introduced situational shifts in word sequences in the form of semantic and perceptual boundaries, with semantic relatedness between words or the frame color around a word changing on a regular basis. After encoding, we tested participants' associative memory performance and false recollection rates. In Experiment 1, color boundaries occurred synchronously or asynchronously to semantic boundaries. We found better associative recognition, but also more false recollections, for synchronous than asynchronous boundaries. In Experiment 2, color boundaries occurred synchronous to semantic boundaries or were absent entirely. We found that false recollection rates elicited by semantic boundaries increased when color boundaries were absent. We also tested associative memory performance using a non-semantic, temporal memory task. We found better temporal memory performance for semantic boundaries, as well as a negative correlation between increased false recollection rates and better temporal memory performance for semantic lists, but not for random lists. We discuss implications for false memory theories and segmentation of narrative materials in false memory research.

Keywords: temporal segmentation, false memories, associative memory, temporal memory

Introduction

In our daily lives, situational contexts shift regularly over time, as we navigate between social situations or spatial environments, tell a story or watch a movie. The human memory system has evolved to encode and store our experiences in accordance to relevant contextual shifts (Bower & Morrow, 1990; Brunec, Moscovitch, & Barense, 2018; James, 1890; Tulving, 1985; Wallenstein, Eichenbaum, & Hasselmo, 1998). For example, experiences that were encoded in the same situational context are subsequently easier to retrieve from memory than experiences that were encoded in different contexts (Godden & Baddeley, 1975; LaBar & Phelps, 2005; Pointer & Bond, 1998). Such mnemonic context effects are suggested to stem from enhanced associative binding between discrete events that share the same contextual features (Clewett & Davachi, 2017; Wallenstein et al., 1998). This mechanism may also underlie encoding of narratives, e.g., stories or movies, in which perceived changes in perspective, scenery or action goals act as situational boundaries that segment the narrative content into distinct situational models in memory (Cohn, 2020; Radvansky & Zacks, 2017; Richmond & Zacks, 2017; Zacks, 2020). Thus, the contextual shifts impose organizational structure in memory by clustering experiences in accordance with the encoded contexts.

One side effect of associative processing in memory is that items are activated in one's knowledge base that were not part of the original experience, but are falsely attributed to or concluded to be part of that experience. This leads to a false sense of remembering an event that did not occur, or did not occur in the remembered context, a phenomenon also called false memory. False memories are generated by the same associative memory mechanisms, and activate the same associative memory areas in the brain, as true recollections (Johnson, Raye, Mitchell, & Ankudowich, 2012; Mitchell & Johnson, 2009; Schacter & Slotnick, 2004; van de Ven, Otgaar, & Howe, 2018). One way to induce false memories is to have participants read or listen to a narrative about a

plausible yet false past event and suggest them that they experienced this event (Hyman & Loftus, 1998; Loftus, 1991, 2005). In addition, false memories can also happen incidentally, when, for example, participants learn semantically related words (e.g., dream, pillow, night, bed, etc) and spontaneously remember a related, but non-presented word (i.e., sleep). This method has been labeled the Deese/Roediger-McDermott (DRM) paradigm (Deese, 1959; Roediger & McDermott, 1995), and creates a mnemonic illusion for semantically related items that were not encoded with the word list. This effect stems from the semantic associations between the individual words in the list and their semantic relation to a not-presented related word, with the likelihood of a false recollection increasing with increasing associative connectivity or similarity between discrete items in memory (Knott, Dewhurst, & Howe, 2012; Robinson & Roediger, 1997). Spontaneous false memories have also been observed for narrative stimuli, in which participants, after reading scripts about actions in known situational contexts, may recall unstated story details that are nonetheless consistent with the situational context (Bower, Black, & Turner, 1979). Further, false memory creation can be facilitated by inserting associatively-related words in narratives and stories, after which participants often-times misremember related but non-presented words linked to the narratives (Otgaar, Howe, Peters, Smeets, & Moritz, 2014). The sensitivity of narratives for false recollections may not be surprising, given the natural recruitment of associative processing to encode and memorize narratives (Brunec et al., 2018; Valerie F. Reyna, Corbin, Weldon, & Brainerd, 2016). There is even some evidence to suggest that narratives are more likely to generate false memories based on suggestion than photographs (Garry & Wade, 2005). However, contrasting findings have been observed in other studies, in which doctored family photographs elicited false memories in a larger proportion of participants than narratives did (Lindsay, Hagen, Read, Wade, & Garry, 2004; Wade, Garry, Read, & Lindsay, 2002). It thus remains unclear how narrative processing contributes to false memory formation.

Situational boundaries could play an important role in false memory, as they facilitate associative processing in memory. According to event segmentation theory (Radvansky & Zacks, 2017; Richmond & Zacks, 2017; Zacks, 2020), boundaries facilitate segmentation of our experiences into discrete event models, in which information is conceptually related within an event and supports prediction about how it will unfold. Furthermore, event models interact with prior knowledge, such that previously encoded experiences of similar situational contexts can be used to update or fill in an event model. The associative binding of information within a situational context is therefore a key process in event segmentation. Indeed, previous studies have shown increased associative memory performance for event information sharing the same context, compared to information encoded in different contexts. For example, when participants watched a series of visual objects that were presented within a colored frame, their memory for the temporal order of object pairs was better when they were encoded in the same color context, compared to different contexts (Heusser, Ezzyat, Shiff, & Davachi, 2018). Similar effects have been observed for visual categorical contexts (DuBrow & Davachi, 2013, 2016), auditory contexts (Huff et al., 2018; Huff, Papenmeier, & Zacks, 2012; van de Ven, Kleuters, & Stuiver, 2021), as well as for spatial (Radvansky & Copeland, 2006; van Helvoort, Stobbe, Benning, Otgaar, & van de Ven, 2020) and timing contexts (Logie & Donaldson, 2021; van de Ven, Jäckels, & De Weerd, 2021). Thus, situational boundaries facilitate associative binding within a context, but impair binding across contexts.

However, it is unclear if and how boundaries affect false memory generation. Contemporary theoretical perspectives on false memory offer different accounts about possible effects of boundaries on false memory production. Spreading activation accounts (Collins & Loftus, 1975; Howe, Wimmer, Gagnon, & Plumpton, 2009) suggest that factors that enhance associative spreading will enhance false memory tendency. As such, situational boundaries would *increase* the proneness to false memory production.

However, it is also possible that contextual boundaries *decrease* false memory tendency. According to Fuzzy Trace Theory (Brainerd, Reyna, Wright, & Mojardin, 2003; V F Reyna & Brainerd, 1998), one could reason that situational boundaries enhance true memory by storing verbatim details of the event. When relying on the specific details of an event at retrieval, this will guard against the formation of false memories, an effect called recollection rejection (Brainerd et al., 2003). A recent computational model based on theoretical propositions of boundary segmentation and event memory was used to segment visual and textual narrative stimuli (Franklin, Norman, Ranganath, Zacks, & Gershman, 2020). The model was able to simulate event memory and false memory-like responses akin to those observed in incidental or spontaneous false memory studies (Bower et al., 1979), which can be interpreted as evidence in favour of the suggestion that boundaries facilitate false memory formation. However, the effect of boundaries on false memory remains to be experimentally tested.

In the current study, we adapted a segmentation paradigm in order to test the effect of boundaries on false memory production. We presented participants with sequences of multiple DRM word lists, in order to elicit semantic boundaries between the last word of a previous list and the first word of the consecutive list. We contrasted the semantic relatedness of DRM lists to another set of lists in which words were randomly shuffled across different DRM lists, thereby effectively breaking the semantic relatedness. Further, to compare semantic boundaries to contextual boundaries of previous studies, we also included perceptual boundaries by changing the color of a frame surrounding each word. In Experiment 1, the semantic boundaries were presented synchronously or asynchronously with the color boundaries, with asynchronous color boundaries resulting from a color change in the middle of a DRM list. We hypothesized that color boundaries would respectively enhance or impair associative processing of the DRM lists when presented synchronously or asynchronously with semantic boundaries, respectively. As a consequence, we

hypothesized that asynchronous boundaries would result in fewer false recollections than synchronous boundaries.

To more directly test the effect of semantic boundaries on associative processing and false memories, we also conducted a second experiment in which color boundaries were present (and synchronous to semantic boundaries) or absent. We also included a temporal memory task in the second experiment that has been shown to rely on temporal contextual binding in associative memory (Jenkins & Ranganath, 2010; Montchal, Reagh, & Yassa, 2019). In addition to replicating findings of Experiment 1, we hypothesized that semantic and color boundaries would improve temporal memory task performance as a consequence of facilitated associative processing. Finally, the independent manipulation of semantic and color boundaries allowed us to test whether boundaries enhanced false recollections, in line with spreading activation theories, or decreased them, in line with Fuzzy Trace Theory.

Method

Experiment 1

Participants

We recruited twenty-three healthy participants from the university population (11 females; mean [SE] age in years = 29.8 [3.2]). Participants were recruited via social media. Sample size was based on a power calculation (G*Power, (Erdfelder, Faul, & Buchner, 1996)) based on effect sizes from previous publications (lower bound=0.65; (DuBrow & Davachi, 2013; van de Ven, Kleuters, et al., 2021); power=0.8, $\alpha=0.05$, minimum estimated N=21). All participants provided informed consent prior to participation and were financially compensated afterwards by €7.50 per hour. The study was approved by the ethics review board of the Faculty of Psychology and Neuroscience.

Materials

We used sixteen intact DRM lists and sixteen lists of randomly shuffled words (hereafter respectively referred to as Semantic and Random lists). Each list comprised eight encoding words and two lure words (we used two, rather than one lure in order to increase the number of trials in the memory tests). We selected thirty-two DRM lists from previous publications (Dewhurst, Anderson, & Knott, 2012; Roediger & McDermott, 1995; Shah & Knott, 2018; Stadler, Roediger, & McDermott, 1999; Wang, Otgaar, Howe, Lippe, & Smeets, 2018). As some of the DRM lists of these studies included emotional words (Dewhurst et al., 2012; Shah & Knott, 2018), we selected eight negative emotional and eight neutral lists to be used as Semantic lists. For the Random lists, we selected another set of eight negative emotional and eight neutral lists, and the items were subsequently randomly shuffled across the lists.

Figure 1. Experimental design. *A: The encoding task comprised a series of thirty-two items from four consecutively presented Random or Semantic word lists. Each word was presented in a colored frame, of which the color could change after every eighth word (synchronous change, Experiments 1 & 2), halfway through the list (asynchronous change, Experiment 1) or not at all (Experiment 2). B: After encoding, memory was tested in an associative memory task (Experiment 1), a word recognition task (Experiment 2) and a temporal position memory task (Experiment 2). In the illustration, the first Semantic list comprised items that were associated to the lure “sweet”. The lure was shown during the associative and word recognition tasks, but not during encoding.*

Procedure

In a within-subject design, participants completed eight blocks of encoding and memory testing tasks. During the encoding task (Figure 1), thirty-two words from four consecutive lists were sequentially presented on a computer screen (2.5s for each word, with a 2s inter-stimulus interval) in uppercase letter format. In four of the eight blocks, all words in the encoding task stemmed from Semantic lists, while in the other four blocks, all words stemmed from the Random lists. List selection and order of presentation were randomized in each block and for each participant, with each list being presented only once to each participant throughout the experiment. Word order was randomized within each list (but not across lists). Each word was presented within a colored frame that changed color in one of two conditions. In the Synchronous condition, the frame color changed after every eight words, starting with the first word (i.e., color changes temporally coincided with list changes). In the Asynchronous condition, the first color change occurred after the fourth word and then subsequently changed after every eight words (i.e., color changes occurred in the middle of a list and a color spanned across two halves of consecutive lists). To maximize attentional encoding, participants rated for each word how pleasurable they found the combination of the

meaning of that word and the frame color, with a maximum response time equal to the duration of the word presented on the screen.

After the encoding task, participants completed an associative recognition task that comprised thirty-two trials. In each trial, a word was shown together with a colored frame and participants had to judge 1) whether they had seen the word-color combination in the previous encoding task (associative recognition judgment), 2) whether they had seen the word irrespective of the frame color (word recognition judgment) or 3) they had not seen the word previously (new judgment). In half of the trials, words were selected from the first or fifth position of each list as shown during encoding (i.e., the target words). In the other half, the lure items of each of the four lists were presented. Lure items were semantically related to the encoded words of Semantic lists, but were not related to the encoded words of Random lists. Trial order of the recognition task was randomized for each repetition of the task and for each participant. Words in the recognition task were presented in lowercase letter format to minimize recognition judgments based on low level perceptual features. Response time was unlimited.

The experiment was programmed in PsychoPy3 (Bridges, Pitiot, MacAskill, & Peirce, 2020; Peirce, 2007), which participants could download and install as open-source freeware on their own computer.

Analysis

Three participants were excluded due to non-compliance with task instructions or very poor performance, leaving twenty datasets for the analyses. Statistical analyses were conducted using Matlab and JASP (JASP Team, 2018). The dependent variable for the encoding task was average response time of the encoding judgments (i.e., pleasantness rating), which was analysed using a 2 x 2 x 2 repeated measures ANOVA with Boundary Synchrony (Synchronous vs. Asynchronous), Item (Boundary vs. Non-boundary words)

and Semantic Relatedness (Semantic vs. Random lists) as within-subject factors. For the Item factor, non-boundary response time was obtained by pooling across positions two through eight. For the recognition task, we analysed associative hit rate (proportion correct of word-color combinations presented during encoding), recognition hit rate (proportion correct of words presented during encoding, irrespective of frame color) and false alarm rate (proportion of seen judgments for lure items). Hit rates were analysed using a 2 x 2 x 2 repeated measures ANOVA with Boundary Synchrony, Item (Boundary vs. Middle) and Semantic Relatedness as within-subject factors. False alarm rate was analysed using a 2 x 2 repeated measures ANOVA with Boundary Synchrony and Semantic Relatedness as within-subject factors. We did not analyse response time of the recognition task as there was no response time limit.

Results

Encoding task

Figure 2 shows averages and 95% confidence intervals of the encoding response times for the eight word positions in Random and Semantic lists during Synchronous or Asynchronous frame color changes. The repeated measures ANOVA with Synchrony, Item and Semantic Relatedness as within-subject factors yielded significant main effects of Synchrony ($F(1,19)=6.47$, $P=0.02$, $\eta_p^2=0.25$) and Item ($F(1,19)=24.03$, $P<0.001$, $\eta_p^2=0.56$), and a significant Synchrony x Item interaction ($F(1,19)=9.07$, $P=0.007$, $\eta_p^2=0.32$). In the Asynchronous condition (Figure 2A), encoding time for the boundary word was higher than for non-boundary words in the Semantic ($T(19)=2.58$, $P=0.018$, Cohen's $d=0.58$), but not the Random lists ($T(19)=1.25$, $P=0.23$). In the Synchronous condition (Figure 2B), the encoding response times for the boundary word was significantly higher than response times for the non-boundary words (pooled across positions 2 through 7) in both the Random ($T(19)=4.02$, $P=0.001$, Cohen's $d=0.90$) and Semantic lists ($T(19)=4.35$, $P<0.001$, Cohen's $d=0.97$). These findings show a boundary

effect during encoding when switching between inherently semantically coherent lists, compared to switching between lists of random words, next to the boundary effect due to frame color changes.

Figure 2. Encoding Results of Experiment 1. Plots show average (bars) and 95% confidence intervals (error bars, as described by (Masson & Loftus, 2003)) of encoding response times for each of the eight positions (P1 through P8) in a Random or Semantic list, when frame color changes occurred asynchronously (A) or synchronously with list changes (B). * $p < .05$, *** $p < .005$.

Associative recognition task

Figure 3A and 3B show the associative recognition accuracy for the boundary and middle words of the Random and Semantic lists in the Asynchronous and Synchronous boundary conditions. A repeated measures ANOVA with Synchrony, Item and Relatedness as within-subject factors yielded a significant Synchrony x Item interaction effect ($F(1.19)=17.55$, $P<0.001$, $\eta_p^2=0.48$), but no significant effects in the other main or interaction effects.

In the Random lists, accuracy was better for the boundary item compared to the middle item in the synchronous boundary condition, which was reversed in the asynchronous boundary condition. A repeated measures ANOVA of Synchrony and Item statistically supported this pattern with a significant Synchrony x Item interaction effect ($F(1,19)=4.43$, $P=0.049$, $\eta_p^2=0.19$), but no significant main effects.

In the Semantic lists, accuracy showed a similar reversal between synchronous and asynchronous conditions, but with an enhanced difference between synchronous and asynchronous accuracy for boundary items. A repeated measures ANOVA supported this pattern of results with a significant main effect of Synchrony ($F(1,19)=5.72$, $P=0.027$, $\eta_p^2=0.23$) and a significant Synchrony x Item interaction effect ($F(1,19)=16.61$, $P<0.001$, $\eta_p^2=0.47$). Posthoc comparisons revealed a significant difference between the accuracy of synchronous and asynchronous boundary items ($T(19)=4.84$, $P<0.001$, Cohen's $d=1.08$), but not for middle items ($T(19)=-0.70$, $P=0.49$). Further, the superior synchronous boundary accuracy for boundary items was significantly larger than for middle items ($F(19)=4.08$, $P<0.001$, Cohen's $d=0.91$).

Figure 3C and 3D show the word recognition accuracy for the boundary and middle words of the Random and Semantic lists in the two boundary conditions. Accuracy was comparably high across all conditions (average [SE] accuracy = 0.81 [0.03], 95% confidence interval = 0.75 – 0.86), with no significant main or interaction effects (repeated measures ANOVA; all P s > 0.09).

Figure 3. Associative recognition results of Experiment 1. Average (bars) and 95% confidence intervals (error bars; (Masson & Loftus, 2003)) for associative (A,B) and word recognition (C,D) hit rates for the Boundary and Middle words of the Random (A,C) and Semantic lists (B,D), when color boundaries occurred asynchronously (Async, black bars) or synchronously (Sync, white bars) with semantic boundaries. * $p < .05$, *** $p < .005$.

False memory responses

Figure 4 shows the false alarm rate for lure words in the recognition task. A repeated measures ANOVA with Synchrony and Semantic Relatedness as within-subject factors yielded significant main effects for Synchrony ($F(1,19)=4.57$, $P=0.046$, $\eta_p^2=0.19$) and Semantic Relatedness ($F(1,19)=5.06$, $P=0.037$, $\eta_p^2=0.21$). False recognition was higher for Semantic lists than for Random lists, and additive to higher false recognition for Synchronous than for Asynchronous boundaries. The interaction effect was not significant ($P>0.7$).

Figure 4. False alarm rates of Experiment 1. For legend, see Figure 4. * $p < .05$, ^a main effect $p < .05$.

Discussion

The findings can be catalogued as follows. First, shifting between semantically coherent word lists resulted in elongated response times during encoding of the first word in a list, similar to the effect of perceptual boundaries (DuBrow & Davachi, 2013; Heusser et al., 2018; van de Ven, Jäckels, et al., 2021). A change in semantic context was thus processed as a contextual boundary during encoding of individual words. Notably, the encoding task required judgments about individual words, but participants likely automatically processed the semantic relation between words.

Second, accuracy for associative color-word memory was better for items encoded at a color boundary than items that were encoded further away. This finding replicates a previous study that also used color boundaries (Heusser et al., 2018). However, a new finding is that color boundaries impaired the associative processing of semantically coherent lists when presented in the middle of those lists, compared to when color boundaries were presented synchronously with semantic boundaries. This finding is in line with suggestions that boundaries structure associative processing in memory (Brunec et al., 2018; Zacks, 2020). Further, the lack of a boundary effect on word recognition memory suggests that boundary-based segmentation affects item-

context associative processing, rather than enhancing item-specific processing in memory (Clewett & Davachi, 2017; Heusser et al., 2018).

Third, we found that semantic and color boundaries enhanced false memory rate. The lack of a significant interaction between semantic and color boundaries on false memory rate suggests that boundaries of different contextual features facilitate associative processing in an independent and additive, rather than multiplicative, manner. That is, associative processing of the color context did not modulate associative processing of semantic coherence. In sum, we suggest that the magnitude of false memory rate is an indication of degree or strength of associative processing in memory, in line with proposals that temporal segmentation facilitates associative processing of items encoded within a context.

A limitation of Experiment 1 was that, as both semantic and color boundaries were presented throughout, the effect of semantic boundaries on associative memory could not be isolated from color boundaries. This is particularly relevant in interpreting the false memory rates. The lower false memory rates for asynchronous boundaries, compared to the synchronous boundaries, in the semantic lists could be explained by opposing views. If a color boundary in the middle of a list interfered with semantic processing, then false memory rate would increase in the absence of color boundaries. However, it is also possible that color boundaries would only affect associative processing when presented simultaneously with semantic boundaries, but not when boundaries occur asynchronously. If so, then absence of color boundaries would not change the pattern of false memory rates for semantic lists.

Further, we wanted to test if semantic relatedness and boundaries would increase associative processing independently of word recognition responses. Previous studies have shown that boundaries enhance temporal associative memory within segmented contexts (Heusser et al., 2018; van de Ven, Jäckels, et al., 2021). Further, semantic relatedness may also enhance temporal associative processing during

encoding (Van Der Meer, Beyer, Heinze, & Badel, 2002) and in memory (Gurguryan, Dutemple, & Sheldon, 2021; Zaromb et al., 2006). Thus, in our task, we would expect that conditions that facilitate false recollection would also show better temporal memory performance.

We addressed these two issues in Experiment 2, in which participants encoded semantic or random lists while color boundaries were either presented synchronously with semantic boundaries or were absent entirely. This design allowed us to assess the effect of semantic boundaries on false memory rates independent of color boundaries. Further, we replaced the associative memory task by a simpler word recognition task, for which participants did not need to recall color context information. We retained the use of semantic lures in the recognition task. Finally, to investigate temporal memory, participants had to indicate the temporal position of words seen during the preceding encoding task. This task taps into temporal associative memory processes involved in segmentation (Clewett & Davachi, 2017) and has been shown to increase brain activity in medial temporal lobe areas (Jenkins & Ranganath, 2010; Montchal et al., 2019). We hypothesized that the increased associative processing due to semantic and color boundaries would lead to better temporal memory performance, but at the cost of higher false memory rates.

Experiment 2

Participants and Methods

We recruited twenty-eight new participants from a university environment (9 females; mean [SE] age in years = 34.5, [3.9]). All participants provided informed consent prior to participation and were financially compensated afterwards.

For this experiment, the PsychoPy code was converted to JavaScript in order to be conducted online in an internet browser using the Pavlovia server

(www.pavlovvia.org; (Bridges et al., 2020)). Participants were invited to complete the experiment via a Qualtrics survey page. No software needed to be locally installed.

The experimental design was similar to that of Experiment 1, with the following changes (see Figure 1). First, in each repetition of the encoding task, the frame color changed every eight words (Color Boundary) or the color at the start of the encoding task remained fixed throughout the task (No Color Boundary). In the latter condition, the frame color was randomly selected at the start of the encoding task with each new repetition. Second, the encoding task was followed by a word recognition task and a temporal position task. In the recognition task, participants saw a series of words and judged of each word whether it was previously seen during the encoding task (Seen response) or not (Not Seen response). Half of the words in the recognition task were selected from the encoding task (positions one and five of each list) and half were selected from the lure items of each list. In the temporal position task, participants saw a series of words and for each word indicated when (i.e., at which serial position) it was shown in the encoding task. All words in this task were selected from the encoding task. Participants indicated their answer on a “rating scale” using the computer mouse or the set of left and right arrow keys. In both memory tasks there was no response time limit.

Analysis

Analysis of the encoding response times was done in the same way as for Experiment 1. For the recognition task, we analysed hit rate using a 2 x 2 x 2 repeated measures ANOVA with Color Boundary (present, absent), Item (Boundary or Middle item) and Semantic Relatedness (Semantic or Random lists) as within-subject factors, and false alarm rate using a 2 x 2 repeated measures ANOVA with Color Boundary and Relatedness as within-subject factors. For the temporal memory task, we calculated absolute temporal error as dependent variable by subtracting the actual temporal position of a word from the participant’s judgment of temporal position and then

discarding the sign of the difference. The absolute temporal error was then analysed using a 2 x 2 x 2 x 4 repeated measures ANOVA with Color Boundary, Item, Semantic Relatedness and List (one, two, three and four) as within-subject factors. We separated rather than pooled the lists of an encoding task in order to analyse the contribution of list serial position. We again did not analyse response times of the recognition task because there was no response time limit.

Results

Encoding

Figure 5 shows averages and 95% confidence intervals of the encoding response times for the eight word positions in Random and Semantic lists during the two boundary conditions. The 2 x 2 x 2 repeated measures ANOVA yielded significant main effects of Color Boundary ($F(1,27)=36.37$, $P<0.001$, $\eta_p^2=0.57$) and Item ($F(1,27)=75.89$, $P<0.001$, $\eta_p^2=0.74$), and a significant Color Boundary x Item interaction ($F(1,27)=43.17$, $P<0.001$, $\eta_p^2=0.62$). Encoding time for the boundary word was significantly higher than for non-boundary words for all conditions (Absent Color Boundary-Random: $T(27)=2.33$, $P=0.027$, Cohen's $d=0.44$; Present Color Boundary-Semantic: $T(27)=4.34$, $P<0.001$, Cohen's $d=0.82$; Absent Color Boundary-Random: $T(27)=7.24$, $P<0.001$, Cohen's $d=1.37$; Present Color Boundary-Semantic: $T(27)=6.85$, $P<0.001$, Cohen's $d=1.29$). However, this effect was larger when frame color changed compared to when frame color remained fixed. Further, within the Absent Color Boundary condition, the effect was larger for the Semantic than for the Random lists, although this difference was not significant ($P=0.23$).

Figure 5. Encoding response times in Experiment 2. Legend similar to that of Figure 2, with the exception that boundary conditions comprised absence (A) or presence (B) of color boundaries synchronous to list changes.

Figure 6. False alarm rates of Experiment 2. False alarm rates for Random and Semantic lists with color boundaries absent (NoBnd, black bars) or present (ClrBnd, white bars). * $p < .05$.

Recognition task: Hit and false alarm rates

In the recognition task, hit rate was high (average [SE] = 0.87 [0.01], 95% confidence interval = 0.85 – 0.89; figure not shown). A 2 x 2 x 2 repeated measures ANOVA yielded no significant main or interaction effects (all P s > 0.16).

Figure 6 shows the false alarm rate, which was higher for the Semantic than the Random lists. This difference was statistically supported by a significant main effect of Semantic Relatedness (repeated measures ANOVA; $F(1,27)=9.28$, $P=0.005$, $\eta_p^2=0.26$). Further, posthoc comparisons showed that, for the Semantic lists, false alarm rate was lower when color boundaries were present, compared to when they were absent ($T(27)=-2.20$, $P=0.036$, Cohen's $d=-0.42$). This difference was not observed in the Random lists ($P=0.78$).

Temporal memory

Figure 7 shows the means and 95% confidence intervals of the absolute temporal error values for the absence or presence of color boundaries in the Random and Semantic lists. The plots show larger absolute temporal error for the Random lists than for the Semantic lists. Further, color boundaries equalized the pattern of temporal error in the Random lists for words at or away from those boundaries. These result patterns are statistically supported by a four-way 2 x 2 x 2 repeated measures ANOVA, which yielded significant main effects of Semantic Relatedness ($F(1,27)=31.38$, $P<0.001$, $\eta_p^2=0.54$) and Item ($F(1,27)=9.82$, $P=0.004$, $\eta_p^2=0.27$), and a significant Color Boundary x Item interaction effect ($F(1,27)=4.31$, $P=0.048$, $\eta_p^2=0.14$).

Figure 7. Temporal position error. Average and 95% confidence intervals (error bars; (Masson & Loftus, 2003)) of absolute temporal error for Boundary and Middle words in the Random (A) and Semantic B) lists in the absence (NoBnd) or presence (ClrBnd) of color boundaries occurring synchronous to list changes.

To further parse the interaction effect, we conducted two three-way 2 x 2 repeated measures ANOVAs with Color Boundary and Item as within-subject factors, for the Random and the Semantic lists separately. In the Random lists, we found a significant main effect of Item ($F(1,27)=4.88$, $P=0.036$, $\eta_p^2=0.15$) and a significant Color Boundary x Item interaction effect ($F(1,27)=5.36$, $P=0.028$, $\eta_p^2=0.17$). Posthoc pairwise comparisons showed that temporal error significantly increased from Boundary to Middle items in the absence of color boundaries ($T(27)=3.46$, $P=0.002$, Cohen's $d=0.65$), but not when color boundaries were present ($P>0.7$).

In the Semantic lists, the repeated measures ANOVA yielded a significant main effect of Item ($F(1,27)=5.58$, $P=0.026$, $\eta_p^2=0.17$). The other main or interaction effects were not significant ($P_s>0.65$). We thus did not find evidence that color boundaries modulated the effect of semantic boundaries on temporal memory for words in the Semantic lists.

Correlations between false alarm rates and temporal memory error

The observations that semantic boundaries enhanced false alarm rates and decreased temporal memory error could indicate that the two tasks relied on a common source of associative processing, in which semantic relatedness enhanced (temporal) associative processing in memory at the cost of an increased false memory risk. If so, then more false alarm rates should be related to smaller temporal memory errors for the semantic lists. This relation should then not exist for random lists, in which false alarm rates reflect random memory errors. In this case, more false alarms would be related to larger temporal memory errors (indicative of generally poorer memory performance).

To investigate this scenario, we correlated false alarm rates with absolute temporal memory errors across participants for the random and for the semantic lists, separately. For the random lists, we found that participants with higher false alarm rates showed larger temporal errors ($r=0.38$, $p=0.046$). For the semantic lists, we found the inverse pattern, in which participants with higher false alarm rates showed smaller temporal errors ($r=-0.34$, $p=0.079$). Further, the two correlations were statistically significantly different (two-sided Z-test; $Z=2.66$, $p=0.004$), which supports a dissociation of associative processing in memory between random and semantically related lists.

Discussion

Experiment 2 replicated and extended our findings of Experiment 1. We found that changes between semantic lists elicited semantic boundaries in the absence of any color boundaries, and also that semantic boundaries enhanced false alarm rates. Moreover, false alarm rates for semantic lists were lower when color boundaries were also present. This finding is in line with a spreading activation account of false memory (discussed in more detail below).

We also found that participants performed better in the temporal memory task after having encoded semantic rather than random lists. This finding fits with previous findings of stronger temporal associative processing for semantically or conceptually

related items (Gurguryan et al., 2021; Van Der Meer et al., 2002; Zaromb et al., 2006), and is in line with the suggestion that semantic relatedness increased associative processing in memory (Knott et al., 2012; Robinson & Roediger, 1997). Moreover, our finding suggests that associative processing of semantic relatedness generalized to associative processing of other contextual domains. This suggestion is supported by the dissociation of a positive vs. negative correlation between false alarm rates and temporal memory error for the random semantic lists, respectively. Finally, in random lists, the synchronous color boundaries equalized temporal memory for words at different positions in a list, suggesting that boundaries provided a scaffold for associative memory formation when other contextual information is lacking.

General Discussion

In sum, our findings suggest an interaction of two components of segmentation underlying false memory generation: Semantic boundaries enhance the tendency for false recollections while additional color boundaries suppress false recollections. Our results can be best explained by a Fuzzy Trace Theory account (Brainerd & Reyna, 2002; Valerie F. Reyna et al., 2016), which would predict that the color boundaries provide an additional, perceptual context that strengthens the verbatim traces of the words and thus decreases false memory formation. The finding of Experiment 1 that asynchronous color boundaries suppressed false recollections is evidence that semantic and perceptual contexts indeed became associated in memory. The encoding of a semantic list with two different color contexts interferes with the associative processing of the semantic relatedness of that list, thereby suppressing false recollections. Further, the lower temporal error rates for semantic lists also fit to this account, as semantic relatedness supported processing of temporal context in memory, thereby strengthening verbatim traces.

Our results are more difficult to explain from a spreading activation perspective (Howe et al., 2009). In light of evidence that perceptual boundaries enhance associative encoding, spreading activation would predict that color contexts synchronous to semantic boundaries facilitate encoding of the semantic relatedness among words and thereby increase the chance that not-presented words are activated during memory retrieval. This view would also propose that synchronous semantic and color boundaries propel true memory rates as well. Our findings are not in line with these predictions. However, we note two caveats in considering spreading activation accounts. First, the relatively high recognition hit rates in our experiments could have masked any increases in true memory as predicted by spreading activation. Second, it is not straightforward from spreading activation accounts how (non-semantic) perceptual contexts would influence semantic relatedness in memory. Spreading activation is most commonly used to explain semantic relatedness in texts, although it has also been used to explain priming effects of non-semantic associations, such as harmonically related music chords (Bharucha & Stoeckig, 1987) or distance related landmarks locations on a map (McNamara, Ratcliff, & McKoon, 1984). Yet, it remains unclear if and how associative processing related to one context affects that of another. To address these issues, future segmentation studies should adhere more closely to the tenets of spreading activation theory.

We also found that encoding of boundary words did not enhance recognition memory for those words, compared to words encoded away from boundaries. Previous studies using a similar segmentation task also did not observe a boundary-related recognition enhancement (DuBrow & Davachi, 2013; Heusser et al., 2018; van de Ven, Kleuters, et al., 2021). In contrast, recognition enhancement for boundary items has often been reported in studies using naturalistic stimuli (Magliano, Miller, & Zwaan, 2001; Schwan, Garsoffky, & Hesse, 2000; Speer & Zacks, 2005; Swallow, Zacks, & Abrams, 2009). One methodological difference is that naturalistic stimuli include

semantic or conceptual relatedness within narrative scenes or events, while the more artificial segmentation task involves a random selection of visual objects that lack semantic coherence. This could implicate that boundary enhancement of recognition memory only works for semantically related event information. However, our findings do not support this notion.

What could our findings say about false recollections in narratives? We suggest that conjunctive semantic and perceptual boundaries enhance associative processing while at the same time protect against false recollections. It has been shown that participants are more likely to segment a narrative when multiple narrative dimensions (e.g., space, time or perspective) change simultaneously (Zacks, Speer, & Reynolds, 2009). Concurrently, stronger narrative boundaries may facilitate conceptual coherence within segmented situational models and enhance associative binding within those models. We argue that narratives enhance false recollections if verbatim information from non-semantic contexts is not available or not encoded well enough, in which case memory traces of segmented situational contexts are retrieved on the basis of the semantic gist of that context. Non-semantic contexts can thus protect against the risk of false memory generation, but only if those contexts occur synchronously with narrative semantic contexts.

In conclusion, we show that semantic segmentation boundaries enhance associative processing in semantic as well as non-semantic (temporal) contexts. Enhanced associative processing facilitates the risk for false recollections, but synchronous perceptual boundaries can mitigate this risk. Our findings appear to be best in line with postulations derived from Fuzzy Trace Theory.

Acknowledgments / Author note

All authors contributed to developing the research ideas. VV and SvdH designed the experiments and analysed the data. SvdH collected the data. All authors contributed to writing and editing the manuscript.

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