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Research Report

No one way ticket from orthography to semantics in recognition memory: N400 and P200 effects of associations

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ABSTRACT

Computational models of word recognition already successfully used associative spreading from orthographic to semantic levels to account for false memories. But can they also account for semantic effects on event-related potentials in a recognition memory task? To address this question, target words in the present study had either many or few semantic associates in the stimulus set. We found larger P200 amplitudes and smaller N400 amplitudes for old words in comparison to new words. Words with many semantic associates led to larger P200 amplitudes and a smaller N400 in comparison to words with a smaller number of semantic associations. We also obtained inverted response time and accuracy effects for old and new words: faster response times and fewer errors were found for old words that had many semantic associates, whereas new words with a large number of semantic associates produced slower response times and more errors. Both behavioral and electrophysiological results indicate that semantic associations between words can facilitate top-down driven lexical access and semantic integration in recognition memory. Our results support neurophysiologically plausible predictions of the Associative Read-Out Model, which suggests top-down connections from semantic to orthographic layers.

1. Introduction

A standard finding in memory research is that word recognition is facilitated by semantic associations (Bentin et al., 1985; Neely, 1976). On the other hand, associations can lead to more error-prone recall or recognition when lure words are associated to items provided in the study list (Geng et al., 2007; Roediger and McDermott, 1995). This so-called false memory effect is one of the best-known associative memory phenomena. It has been investigated in many studies using

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the “DRM paradigm”, originally developed by Deese (1959) and modified by Roediger and McDermott (1995). In this procedure, a study list contains words that are associated with a new critical item. In a test phase, participants typically recall the critical item or falsely recognize it among a list of distracter items (Geng et al., 2007).

Recent work has used the classical method of *free association* to assess semantic associations between words (e.g., Roediger and McDermott, 1995). In this paradigm, a stimulus word is presented (e.g., chair) and participants are asked to name as quickly as possible the first words that come to mind (e.g., table). These words are then considered to be semantically associated (Jung, 1905). Two problems are related to this methodology. First, already Jung (1905) defined free associations as a type of human performance that is dependent on cognitive processes, therefore utilizing such performance measures (i.e. dependent variable) as an independent variable to predict human performance may be seen as circular (see Hofmann and Jacobs, 2014). Second, as the method of free association depends on explicit individual reporting, it may well miss a certain number and/or certain types of associations between words (Hofmann and Jacobs, 2014). Such doubts are in line with McKoon's and Ratcliff's (1992) findings, showing that the presentation of a prime word that has not been among the first ones produced in the free association task, can well facilitate the processing of a target word. Therefore it is questionable whether the free association task is suited to provide data accounting for all semantic associations between all words (Hofmann and Jacobs, 2014; McKoon and Ratcliff, 1992).

A straightforward solution to these problems is to define associations by co-occurrence statistics (see below) and use results as input for computational models such as Interactive Activation Models (IAMs; McClelland and Rumelhart, 1981). In these models, perception results from parallel excitatory and inhibitory interactions of detectors for visual features, letters and words as well as for higher levels of processing that provide “top-down” input to the word level (McClelland and Rumelhart, 1981).

While IAMs already successfully predicted human performance in task requiring the implicit retrieval of orthographic word forms from memory (Grainger and Jacobs, 1996), the Associative Read-Out Model (AROM) was the first IAM adding an implemented semantic layer for tasks in which memory is explicitly required (Hofmann et al., 2011). The AROM follows the idea that words, which co-occur in the same linguistic context, are related in meaning. It assumes that two words are semantically associated, if they co-occur significantly more often together in sentences than predicted by chance (Dunning, 1993; Nystrom and McClelland, 1992), which reflects a Hebbian-learning approach by defining semantic associations of items by their frequent common occurrence (Hebb, 1949).

In the recognition memory task participants learn stimuli in a study phase and discriminate these old words from new words in a test phase. The AROM predicts that the occurrence of a particular word (e.g., TABLE) increases the lexical activity of semantically associated words (e.g., CHAIR). Therefore, its semantic activation is stronger resulting in an increase of “old” responses in old and new items in the recognition memory task (Hofmann et al., 2011).

Hence, the AROM can also account for the false memory effect (Hofmann et al., 2011), but it was an open question, however, whether it can also account for response time data – i.e. a standard model fit criterion of IAMs (e.g., Coltheart et al., 2001; Grainger and Jacobs, 1996; Jacobs and Grainger, 1992, 1994; Perry et al., 2007). In this context, the multiple read-out model (MROM) followed the semistochastic IAM (SIAM, Jacobs and Grainger, 1992) in successfully simulating response time distributions for “yes” and “no” responses in lexical decisions as a function of lexical activation (Grainger and Jacobs, 1996). For instance, a large orthographic neighborhood increases lexical activation, predicting faster response times during lexical decision for “yes” responses (Andrews, 1989, 1992, 1997; Carreiras et al., 1997; Forster and Shen, 1996; Grainger and Jacobs, 1996; Sears et al., 1995). The dynamic deadline account of the MROM assumes that a “no” response is generated if not enough evidence for a “yes” response is aggregated before a temporal criterion is reached (Grainger and Jacobs, 1996). In this case, greater lexical activation decreases response probability for correct “no” decisions (Jacobs et al., 2003). In analogy, one can expect a similar response pattern for recognition memory, when lexical activation is driven by semantic associations instead of orthographic neighborhood.

Other recent studies related this hypothetical overall lexical activity elicited by words and nonwords of different neighborhood size to brain activity (e.g., Binder et al., 2003; Braun et al., 2006, 2015; Holcomb et al., 2002). In a combined computional modeling/EEG study, Braun et al. (2006) showed that greater lexical activity as a function of large orthographic neighborhood of a nonword increased N400 amplitudes. Holcomb et al. (2002) also explained the orthographic neighborhood effect in word stimuli by greater lexical activation. This assumption is in line with Mueller et al. (2010) findings, who investigated whether the N400 effect of orthographic neighborhood size is due to lexical-semantic activation. They found similar N400 effect patterns of orthographic and associative neighborhood density and suggested that both N400 effects may originate from a common set of neural generators and that they are also functionally equivalent. However, the most prominent feature of the N400 is probably that it is affected by semantic processing load from contextual facilitation (Chwilla et al., 1995; Kutas and Hillyard, 1984; Kutas and Federmeier, 2011). It is less negative when a word has many semantic associations to the words in sentence context (e.g., Kutas and Hillyard, 1984; cf. Hofmann and Jacobs, 2014) and is sensitive to repetition and semantic priming (Chwilla et al., 1995; Friedman and Johnson, 2000; Kutas and Federmeier, 2011; Lau et al., 2008).

Because the N400 is sensitive to lexical activity, semantic processing and repetition, it should also be affected by semantic associations in the recognition memory task. We therefore expected that the N400 is less negative for words with many associates in the stimulus set as well as for words that have been previously exposed in the study phase (reviewed in Friedman and Johnson, 2000).

While the N400 effect is well replicated and serves as an established indicator for semantic processing in the current state of research, it is uncertain whether semantic associations also influence earlier ERP time windows. Some priming studies showed semantic effects on the N250 and N400 components (Midgley et al., 2009; Morris et al., 2007). These authors proposed that such early effects might reflect facilitatory connections between lexical and semantic components or even a modulation of the interactivity between lexical and prelexical form representations during target word processing (see also Hofmann et al., 2009). Hauk and Pulvermueller (2004) suggested that the earliest word frequency effect on event-related potentials represents an upper limit for the latency of lexical access. Finally, Dambacher et al. (2006) observed word frequency effects in the P200, suggesting that this is the time window in which access to orthographic representations takes place.

For the sake of simplicity, the AROM was originally implemented without a top-down connection from the semantic to the orthographic layer to account for recognition memory (Hofmann et al., 2011). However, in a later version of the model, a top-down feedback connection from the semantic to the orthographic level was proposed to be a plausible extension option (Hofmann and Jacobs, 2014). If this is correct, the P200 should be influenced by semantic associations in a recognition memory task, indicating faster lexical access driven by greater top-down semantic activation.

1.1. *The present study*

To replicate and extend Hofmann et al. (2011) study, we used essentially the same stimulus set as in the previous work. Participants were asked to learn 80 words in a study phase. These old words had to be discriminated from 80 new words in a later test phase (see Fig. 1), while 32-channel EEG was recorded. Words had either many (at least eight) or few (less than eight) semantically associated words in the stimulus set. They were considered to be associated when they occurred more often together in online newspapers or articles than predicted by chance (Dunning, 1993). We conducted 2×2 analyses of variance (ANOVA) for repeated measures for response time and accuracy (number of errors) with the factors oldness (old vs. new) and number of associations (few vs. many). For the electrophysiological analyses we ran separated ANOVAs for the midline and lateral electrodes, following Holcomb et al. (2002). Midline ANOVAs contained the factors oldness and number of associations, whereas lateral ANOVAs included the experimental factors oldness, number of associations as well as the topographical factors anteriority (anterior vs. central vs. posterior) and laterality (left vs. right). To follow up significant interactions of topographical factors with oldness and/or number of associations, post-hoc t-tests were conducted.

In summary, the main aim of our study was to test the predictions derived from the AROM. We expected not only to replicate the facilitatory influence on old words with many semantic associates in error data observed previously, but also on response time data. The reverse effect was expected for false memory of new words: error rates and response times should increase with the number of semantically associated items in the stimulus set. Furthermore we specifically hypothesized associative semantic effects on event-related potentials. IAMs already have been used to explain N400 variance by orthographic familiarity or lexical competition processes in nonwords, but not in words. Because of the AROM's implementation of the semantic layer, we expected to exposure N400 effects in words (Braun et al., 2006; Hofmann et al., 2008). We also expected semantic driven P200 effects, indicating top-down connections from semantic to orthographic layers.

2. Results

2.1. *Behavioral results*

To investigate effects of the factors oldness (old vs. new) and number of semantic associations in the stimulus set (few vs. many), we calculated 2×2 ANOVAs for repeated measures

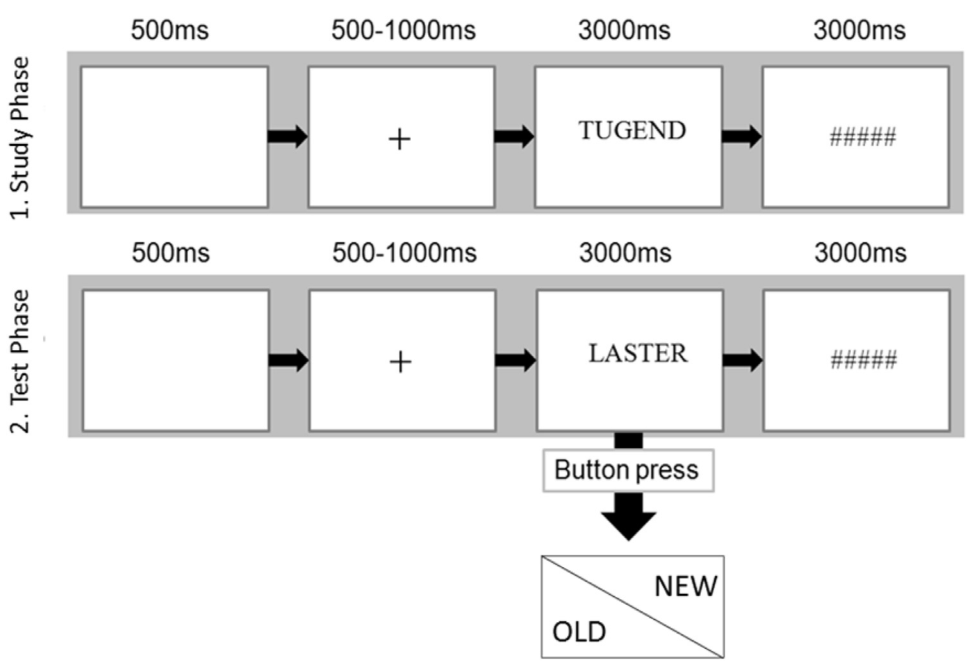

Fig. 1 – Time course of the stimulus presentation on the screen in the study and the test phase.

and post-hoc t-tests for paired samples for accuracy (amount of errors) and response times. Effect size is reported using eta-square (η^2).

2.1.1. *Accuracy*

Accuracy for each word condition was indexed by the number of errors (incorrect rejection of old and incorrect recognition of new words). A 2 × 2 ANOVA for repeated measures showed no main effects of the factors oldness ($F(1,28)<3$) and number of associations in the stimulus set ($F(1,28)<1$), but a significant interaction ($F(28)=25.03$, $p=0.000$, $\eta^2=0.47$). Old words with a small number of semantic associations led to significantly more errors ($t(28)=3.61$, $p=0.001$) than old words with many semantic associates (descriptive statistics see Table 1). Whereas new words with few semantic associations led to significantly fewer errors than new words with a large number of semantic associations ($t(28)=-3.94$, $p=0.001$,see Fig. 2).

2.1.2. *Response times*

Response times were not included in the analyses, when they reflected incorrect responses and when they fell beyond the mean plus/minus 2.5 standard deviation criterion for each subject and condition. Trials excluded as outliers amounted to 16 (1.82%) in the old/few condition, 17 (1.78%) in the old/many condition, 19 (1.9%) in the new/many condition and 16 (1.72%) in the new/few condition.

A significant main effect of oldness was found ($F(1,28)=10.92$, $p=0.003$, $\eta^2=0.28$), along with a significant interaction of oldness and number of associations ($F(1,28)=21.83$, $p=0.000$, $\eta^2=0.43$), but there was no main effect of number of associations ($F(1,28)<1$). Old words with many semantic associates elicited significantly shorter response times ($t(28)=2.77$, $p=0.01$) than old words with few semantic associates (Table 1). For new words this effect reversed: new words with a large number of semantic associations produced significantly longer response times ($t(28)=-4.01$, $p=0.000$) than new words with a small number of semantic associations (see Fig. 3).

2.2. *Neurophysiological results*

A clear positive amplitude was evident around 150 ms after stimulus onset. This P200 was larger for old words and for words with many semantic associations (see Fig. 4). The P200 was followed by a broadly distributed negativity around 400 ms. This N400 was larger for new words and for words with few semantic associations. For midline analyses we examined effects of oldness (old vs. new) and number of associations (few vs. many). For lateral analyses we additionally examined effects of laterality (left vs. right) and anteriority (anterior vs. central vs. posterior), within 320 and 500 ms (N400) and within 150 and 215 ms (P200).

Table 1 – Descriptive statistics of the behavioral results.

Oldness	Number of associations	Response time	Accuracy (error rate)
Old	Few	1170.55 (171.71)	11.14 (4.65)
	Many	1116.15 (194.87)	8.38 (4.76)
New	Few	1214.63 (174.22)	6.89 (3.69)
	Many	1289.75 (204.56)	9.38 (3.76)

Mean values and (standard deviation) of response time (ms) and accuracy (error rate).

2.2.1. *N400*

2.2.1.1. *N400 midline analysis*. For the midline electrodes, we observed a significant main effect of oldness ($F(1,28)=60.443$, $p=0.000$, $\eta^2=0.683$) and a significant main effect of number of associations ($F(1,28)=12.495$, $p=0.001$, $\eta^2=0.309$) but no interaction of oldness and number of associations ($F(1,28)<1$). Old words and words with many associations elicited smaller N400 amplitudes than new words and words with a small number of associations on the midline electrodes (Fig. 4).

2.2.1.2. *N400 lateral analysis*. ANOVA with the factors oldness, number of associates, laterality and anteriority indicated a significant main effect of oldness ($F(1,28)=60.907$, $p=0.000$, $\eta^2=0.685$). Overall, new words elicited higher N400 amplitudes than old words. Moreover, we found a significant main effect of number of associations ($F(1,28)=22.129$, $p=0.000$, $\eta^2=0.441$)

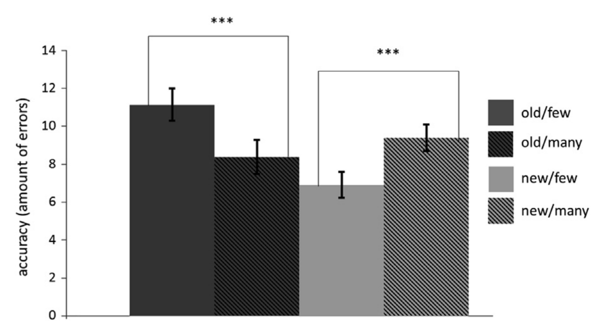

Fig. 2 – Mean error rates (accuracy) for the four conditions old/few, old/many, new/few and new/many and their standard mean errors (old/few: SEM=0.86; old/many: SEM=0.88; new/few: SEM= 0.69; new/many: SEM=0.69).

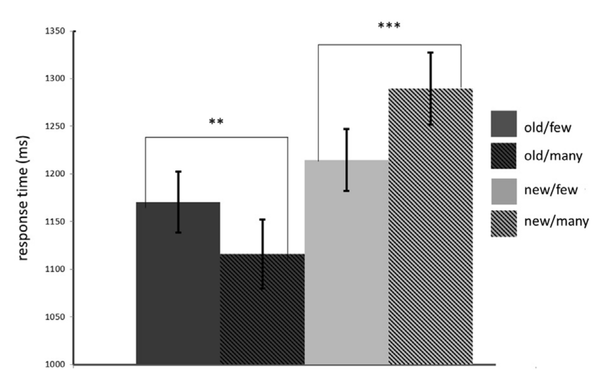

Fig. 3 – Mean response times for the four conditions old/few, old/many, new/few and new/many and their standard mean errors (old/few: SEM=31.89; old/many: SEM=36.19; new/few: SEM=32.35; new/many: SEM=37.89).

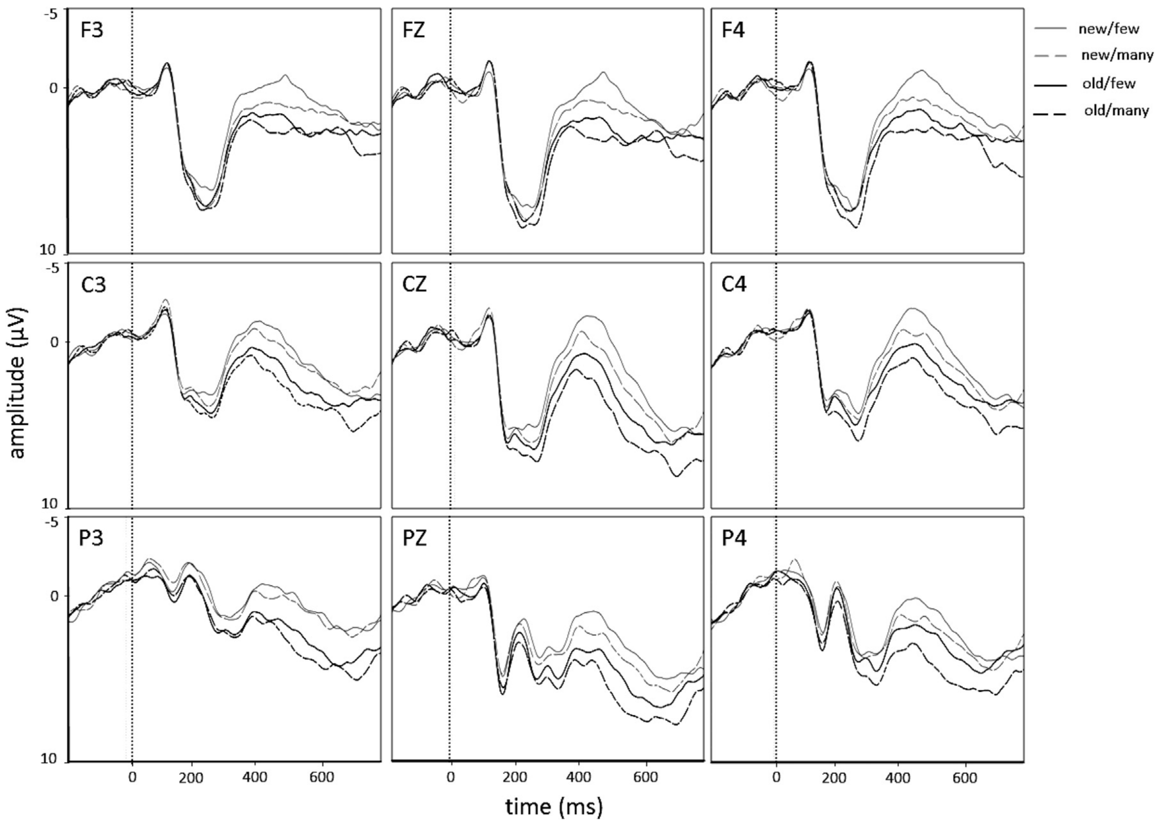

Fig. 4 – Event-related potentials (grand averaged across all subjects) for correct responses on nine representative electrodes, showing the contrast between words with many (at least 8) and words with few (less than 8) associations for old and for new words. Negative voltage is up.

and a significant three-way interaction of the factors laterality, anteriority and number of associations ($F(1.836,51.418)=3.944$, $p=0.025$, $\eta^2=0.123$). Words with few associations revealed higher N400 amplitudes than words with a large number of associations (Fig. 4). To follow up the significant three-way interaction we tested the simple effect of number of associations (many vs. few) in all six lateral regions. To compensate for the problem of alpha inflation in a number of n post-hoc tests, the critical p-value was set to .009 (six comparisons, Sidak correction). Number of associations showed a significant effect in the anterior areas (anterior-right: $t(28)=4.66$, $p=0.000$, anterior-left: $t(28)=5.12$, $p=0.000$). However in the central and posterior areas number of associations revealed only significant effects on the left sites (central: $t(28)=4.238$, $p=0.000$, posterior: $t(28)=3.287$, $p=0.003$) but not on the right posterior cluster $t(28)=1.47$, $p=0.152$). The right central cluster did not surpass the Sidak adjusted significance criterion ($t(28)=2.745$, $p=0.01$), To further explore the interaction with laterality, we compared the amplitude differences corresponding to the number of associations (many – few) pairwise between the left and right sites in the anterior, central and posterior areas. None of the left/right differences reached significance (anterior: $t(28)=1$, $p=0.322$, central: $t(28)=-0.531$, $p=0.599$, posterior: $t(28)=-1.779$, $p=0.086$). Number of associations comparisons revealed greater N400 effects on the anterior sites, getting smaller with the degree of posteriority. Other interactions of the topographic factors with the experimental factors oldness and/or number of associations revealed no significant results.

2.2.2. P200

2.2.2.1. P200 midline analysis. Analyses of the P200 (150–215 ms) revealed a significant main effect of oldness ($F(1,28)=18.195$, $p=0.000$, $\eta^2=0.39$) and a significant main effect of number of associations ($F(1,28)=6.597$, $p=0.016$, $\eta^2=0.19$) but no significant interaction of oldness and number of associations ($F(1,28)<1$). Overall, old words and words with a large number of associations revealed higher P200 amplitudes on midline electrodes than new words and words with a small number of associations (s. Table 2).

2.2.2.2. P200 lateral analysis. For the lateral site analysis, the ANOVA with the factors anteriority, laterality, oldness and number of associations revealed a significant oldness main effect ($F(1,28)=22.521$, $p=0.000$, $\eta^2=0.446$) and number of associations main effect ($F(1,28)=30.13$, p=.011, $\eta^2=0.211$) but no interaction of the factors oldness and number of associations ($F(1,28)<1$). Overall old words and words with a large number of associations elicited higher P200 amplitudes than new words and words with a small number of associations. For the P200 lateral analysis, interactions of the topographic factors with the experimental factors oldness and/or number of associations revealed no significant results (Table 3).

Table 2 – Descriptive statistics of the electrophysiological results for midline analysis.

Middle analysis	Oldness	Number of associations	P200		N400	
Middle	Old	Few	5.08	(3.76)	1.76	(3.46)
		Many	5.86	(3.74)	2.84	(2.99)
	New	Few	4.14	(4.38)	−0.11	(3.05)
		Many	4.69	(3.69)	0.66	(2.88)

Mean values and (standard deviation) of the event-related potentials (μV) P200 and N400 for the midline analyses.

Table 3 – Descriptive statistics of the electrophysiological results for lateral analysis.

Lateral analysis: electrode site	Oldness	Number of associations	P200		N400	
Right-Anterior	Old	Few	5.08	(2.73)	0.92	(2.63)
		Many	5.71	(3.01)	1.93	(2.6)
	New	Few	4.51	(3.26)	−0.19	(2.81)
		Many	5.17	(3.26)	0.61	(2.75)
Right-Central	Old	Few	2.46	(3.09)	0.32	(3.14)
		Many	2.90	(2.96)	1.15	(2.72)
	New	Few	1.59	(3.4)	−0.89	(2.79)
		Many	2.02	(3.12)	−0.58	(3.08)
Right-Posterior	Old	Few	−2.03	(3.73)	−0.43	(3.81)
		Many	−1.81	(3.74)	0.10	(4.24)
	New	Few	−2.77	(3.75)	−1.35	(3.94)
		Many	−2.51	(3.89)	−1.14	(4.22)
Left-Anterior	Old	Few	5.32	(2.61)	0.84	(2.93)
		Many	6.12	(3.01)	1.85	(3.03)
	New	Few	5.01	(3.2)	−0.23	(3.11)
		Many	5.19	(2.76)	0.34	(2.86)
Left-Central	Old	Few	3.03	(3.02)	0.26	(3.46)
		Many	3.63	(2.94)	1.19	(3.03)
	New	Few	2.29	(3.22)	−1.02	(3.05)
		Many	2.57	(2.63)	−0.63	(2.9)
Left-Posterior	Old	Few	−0.23	(4.10)	0.31	(3.87)
		Many	0.19	(4.08)	1.26	(4.04)
	New	Few	−0.66	(4.22)	−0.41	(3.99)
		Many	−0.52	(4.03)	−0.03	(4.02)

Mean values and (standard deviation) of the event-related potentials (μV) P200 and N400 for the lateral analyses.

3. Discussion

We not only again confirmed our earlier results of an increased amount of "old" responses in old and associated items in the recognition memory task (Hofmann et al., 2011), but also found novel response time effects: When a word is associated with many other words within the stimulus set, responses were facilitated in old words but inhibited in new words. In analogy to this, error rates were increased in new words but decreased in old words as a function of semantic associations. Taken together, these behavioral results indicate that semantic associations do not have an overall positive or negative effect on recognition memory performance. Instead, they appear to either help or hinder recognition, depending on whether the word has been studied or not. In addition, electrophysiological results revealed effects of semantic associations from 320 to 500 ms and from 150 to 215 ms, indicating that the number of associated items in the stimulus set affects semantic integration and lexical access to orthographic representations, as predicted by the AROM.

The behavioral results revealed that "old" responses are driven by semantic associations between both old and new words. We suggest that the effect of semantic associations on new words reflects a false memory effect (Roediger and McDermott, 1995), showing increased false recognition rates of new words with many semantic associations in comparison to new words with a smaller number of associations. In contrast, for old words the number of semantic associations boosted recognition memory performance by increasing correct "old" responses. The results reported here support the predictions of the AROM, suggesting that an associative layer with semantically associated words is activated during word perception with associative activation spreading over several word representations. As a consequence, overall lexical activity increases for associated words (Hofmann et al., 2011; Hofmann and Jacobs, 2014; Kuchinke et al., 2013).

But how can the novel response time effects be explained? For orthographic processing, according to the MROM a positive "yes" decision is given when lexical activation reaches a criterion, which is based on the individual word representation in memory (Grainger and Jacobs, 1996). On the other hand, a second decision criterion can also be reached, which is based on the global lexical activity produced by all partially activated word units. While the MROM applies only to orthographic processing, the same prediction holds for semantic activation in the AROM. In analogy to the "yes" response in lexical decision, higher semantic activity facilitated "old" decisions (and therefore correct responses) for old words with many semantic associations in comparison to old words with few associations in recognition memory.

Moreover, the MROM can also provide a mechanism to account for the inhibitory response time effects observed for "new" responses to new words with a large number of semantic associations. Recent studies showed that in lexical decision, a "no" response to nonwords is inhibited when they have many orthographic neighbors (Braun et al., 2006; Grainger and Jacobs, 1996). Nonwords with many neighbors generate greater lexical activity, which prolongs the temporal deadline and leads to slower correct "no" responses (Braun et al., 2006; but cf. Dufau et al., 2012; Wagenmakers et al., 2008). We suggest that the same decision mechanism applies to correct "new" decisions in recognition memory. The higher global lexical activation for new words with many semantic associations delayed the temporal deadline (Jacobs et al., 2003) and therefore increased response times.

The N400 amplitude for correct responses was more negative for new words and for those with few semantic associations. Another prominent feature of the MROM is that it allows to quantify a hypothetical evidence variable or familiarity dimension (Jacobs et al., 2003). While none of the early, mathematical models of word recognition directly quantified the evidence variable central to signal-detection theory (Broadbent, 1967; Morton, 1969; Treisman, 1978; see Jacobs et al., 2003), the MROM evidence variable or familiarity dimension is computed by the sum of activity across all word units at a given cycle of processing time (Grainger and Jacobs, 1996; Jacobs and Grainger, 1992; Jacobs et al., 1998, 2003).

It is assumed that familiarity-based recognition takes place very quickly and automatically, and that it does not necessarily involve explicit recollection of the study phase (Rugg and Curran, 2007). In this context, the event-related potential FN400 as a negative-going potential on the frontal sites, has been proposed to indicate familiarity. In contrast, the N400 has generally been related to semantic processing, even though both components share many features with regard to morphology, timing and response patterns (Voss and Federmeier, 2011). Voss and Federmeier (2011) compared the N400 and FN400 directly and showed that they are not functionally distinct from each other.

In conjunction with the behavioral evidence, we therefore assume that the N400 also provides an electrophysiological signature of stimulus familiarity, based on the lexical activity elicited by a target word (Braun et al., 2006). While Braun et al.'s MROM-based simulation study showed this relation between orthographic lexical activation and the N400 for correct “no” responses during lexical decision, the present study indicates that the same N400 effect is apparent for correct “new” responses in new words during recognition memory. Much like for orthographic activation in the MROM, the AROM predicts decreased N400 amplitudes for words producing greater semantic activation. In contrast to the MROM, however, the AROM successfully predicts the same N400 response pattern for correct “old” responses to old words. It is consequently the first IAM predicting N400 effects in word stimuli by computationally capturing the essential feature of words, i.e. they carry meaning (Coltheart et al., 2001; McClelland and Rumelhart, 1981; Perry et al., 2007, 2010).

A point that needs to be discussed further is that recent studies showed that greater lexical activity induced by orthographic neighborhood leads to larger N400 amplitudes for words (Holcomb et al., 2002) and nonwords (Braun et al., 2006) in lexical decision tasks. Moreover, also in lexical decision, Mueller et al. (2010) found larger N400 amplitudes for words with both many orthographic and associative neighbors. In our recognition memory study, greater lexical activity induced by semantic associations decreased N400 amplitudes, raising the question how these different N400 patterns can be interpreted. Using a lexical decision task, Hofmann et al. (2008) showed that the N400 amplitude increases with the amount of orthographic competition and discussed whether the N400 reflects lexical competition, while Hill et al. (2005) argued that higher N400 amplitudes might reflect deeper processing of a stimulus.

It is not clear, however, whether the inverted effect of orthographic and semantic activation on the N400 are due to different task requirements (lexical decision vs. recognition memory). Molinaro et al. (2010) argued that different processes like the recognition of a word and semantic processing are operated by the brain in a similar time window, i.e. the N400. Furthermore, Binder et al. (2003) suggested that lexical decision for words and nonwords activate different brain areas, as a critical distinction between words and nonwords is that words require access to semantic information. Therefore, it is possible that the N400 reflects different neurocognitive processes: lexical competition and/or familiarity, depending on the task requirements and on whether semantic information has to be accessed. The larger N400 amplitudes observed in previous studies (i.e. Braun et al., 2006; Holcomb et al., 2002; Mueller et al., 2010) were possibly induced by lexical competition processes in lexical decision tasks, while the decreased N400 amplitudes in the current study can perhaps be best explained by familiarity evaluation and semantic processing in recognition memory.

The main effects on the P200 are congruent with the predictions of the AROM in the version proposed by Hofmann and Jacobs (2014), featuring top-down processes from semantic to orthographic layers and in line with studies that showed semantic effects on early ERPs (Midgley et al., 2009; Morris et al., 2007). The P200 amplitude was larger for old words in comparison to new words and for words with many associated items in comparison to words with few semantic associations. Because a similar time frame applies to word frequency effects, Hauk and Pulvermueller (2004) suggested that the P200 reflects an upper time limit for the access to a hypothetical mental lexicon (Dambacher et al., 2006). Some studies showed word frequency and lexicality effects in a time range from 300 to 500 ms (e.g., Barber et al., 2004; Brown et al., 1999; Rugg, 1990; Van Petten and Kutas, 1990). However, there is also a substantial body of work suggesting earlier time windows (Assadollahi and Pulvermueller, 2001; Dambacher et al., 2006; Hauk and Pulvermueller, 2004; Pulvermueller et al., 1995; Sereno et al., 1998).

As in our data the P200 was modulated by semantic associations, we assume that this is the point of time (150–215 ms) when lexical access started. Our P200 effects indicate that the interactivity principle holds true for both orthographic and semantic representation levels (McClelland, 1993): Semantic top-down processes influence word recognition and semantically induced lexical activity speeds up lexical access during recognition memory.

We are aware of the possibility that our results might be modulated to some extend by semantic feature overlap.

Because the present study manipulated the amount of associations of the stimulus words to the other words in the experimental context, it stands in the tradition of theories proposing direct associative links between symbolic representational units (e.g., Anderson, 1983; Collins and Loftus, 1975). To our knowledge we propose the first computationally explicit cognitive process model within this tradition that offers a potential definition of long-term associations between all words by relying on co-occurrence statistics. So far, other co-occurrence-based models of semantics have relied on defining the meaning of a word by latent factors determining with which words they co-occur (e.g., Griffiths et al., 2007; Landauer and Dumais, 1997). This representational assumption is well in line with developmental models of semantic representations, which distribute the meaning of a word across subsymbolic ‘hidden’ representations (e.g. McClelland and Rogers, 2003; Seidenberg and McClelland, 1989).

When aiming to alternatively explain our findings based on such distributed representations, we might assume that words that often co-occur in similar sentence contexts are more likely to share similar semantic features. When a non-studied word is retrieved that has many associates in the stimulus set, this might increase the probability for some of its features to match the features of a learned word, which in turn might elicit false memories, for instance (cf. McClelland and Chappell, 1998; Shiffrin and Steyvers, 1997). However, even for relatively simple semantic priming tasks, in which only two words are taken into account, Hutchison's (2003) review concludes that testing direct associations vs. feature overlap is extremely difficult. Apparently this problem scales up when semantic associations between the 160 stimuli of the present study are to be considered.

While the MROM is able to represent objective form features at the feature, letter, and orthographic layers, the AROM does not explicitly represent the amount of common semantic features between two words (Grainger and Jacobs, 1996; Hofmann et al., 2011). However, following the idea that the meaning of a word is determined by its surrounding context (Firth, 1957; Harris, 1951; Hofmann and Jacobs, 2014), each common associate can also be viewed as a common semantic feature of the two words (Hofmann and Jacobs, 2014). Envisioning an AROM with a more complete associative lexicon (and not only the contextual associations), the dynamic co-activation of such semantic features can be simulated. When the associates of a first stimulus become active, these semantic features might increase the associative activation of the second word, therefore increasing retrieval probability. As a consequence we think that future extensions of the AROM architecture might provide a theoretical framework capable of accommodating both perspectives.

3.1. *Conclusions and outlook*

The similar result patterns of the N400 and the correct recognition of old words and incorrect recognition of new words appear to indicate that they are associated via the same recognition mechanism, i.e. familiarity. We assume that semantic associations produce higher activity in a hypothetical mental lexicon, which leads to a higher stimulus familiarity. This is accompanied by smaller N400 amplitudes due to less effort of semantic processing (Hill et al., 2005) and increased recognition rates for old and new words. However, for new words with a large number of semantic associations the increased lexical activity is linked to longer response times for correct responses and higher error rates. We believe that the response time effects can be explained by a temporal deadline account. Furthermore, we assume that during the time period towards the prolonged temporal deadline for new words with many semantic associations a more difficult decision process takes place that is dependent on a low familiarity. The early association effect on the P200 indicates that semantic associations can speed up lexical access and therefore the semantic integration of words. Even though a clear pattern of results emerged from this work, we acknowledge that accounting for potential modulating effects of semantic feature overlap remains a task for future research. In conclusion, we confirmed the revised version of the AROM (Hofmann and Jacobs, 2014) and, more generally, our results contribute new evidence to model-guided neurocognitive research addressing the importance of semantically driven top-down processes in recognition memory. The new data motivate the development of a slightly more complex model with a new parameter to be fitted, accounting for the apparent top-down connection from semantic to orthographic layers.

We take seriously Barber and Kutas (2007) challenge to utilize EEG measures for constraining computational models of explicit and implicit memory. As the AROM succeeds in accounting for a wide range of electrophysiological and behavioral findings, it provides a powerful tool for further research on the interplay of orthography and semantics in recognition memory. A promising next step in this agenda could be the use of this approach for the examination of implicit memory tasks.

4. Experimental Procedures

4.1. *Subjects*

Behavioral and electrophysiological data were collected for 32 right-handed subjects. Three subjects were excluded because of excessive EEG artifacts, leading to an insufficient number of usable trials (at least 15 per condition). The mean age of the remaining 29 subjects (20 female) was 22.5 years (SD=3.39; range: 18–29). Participants were recruited from the University of Wuppertal community and received course credit if they were students. All subjects reported to have normal or corrected-to normal vision, to be native German speakers, and to have no history of psychiatric or neurological disorders and no reading disabilities.

4.2. *Stimuli*

The stimulus set was taken from an already published study of Hofmann et al. (2011) and consisted of 160 German nouns. The stimuli were taken from the word corpus of the “Leipzig Wortschatz” project (status: December 2006, Quasthoff et al., 2006), which is based on 800 million tokens and 43 million sentences extracted from online newspapers (1992–2006). A substantial number of word features like frequency, length, arousal, imageability and orthographic neighbors were controlled for the stimulus set (see Hofmann et al., 2011). Two words were considered associated when they occurred significantly more often together in the sentences than predicted by their single-occurrence frequency (Dunning, 1993). More specifically, words were defined to have many semantic associations, if they had at least eight associated words and to have few associations, if they had less than eight associated words in the stimulus set. The word sample was split into four conditions, each of 40 nouns, in a 2×2 design including the factors oldness (old vs. new) and number of associations (few vs. many).

4.3. Procedure

80 words were presented in randomized order during the initial study phase. These old words had then to be discriminated from 80 new words in the test phase. Accordingly, the instruction focused on learning the word presented in the study phase and later, during the test phase, decide which word had been shown in the first part of the experiment. Two buttons on a keyboard designated "old" vs. "new" served to record manual responses with hand assignment (left or right button press for old/new responses), counterbalanced across participants. Stimuli were displayed using Presentation 9.9 software (Neurobehavioral Systems Inc., Canada) on a 1020×768, 75-Hz screen, at a viewing distance of about 70 cm. For familiarization purposes, participants saw five exercise trials at the beginning of both study and test phase. In the study phase, three primacy and three recency stimuli were presented.

In the study and test phase, each trial began with a fixation cross presented in the center of the screen for 500–1000 ms (time randomized), followed by the presentation of the word in capital letters for 3000 ms. Participants were instructed not to blink during the presentation of fixation mark and target words to avoid artifacts during the critical registration phase. In the test phase participants had to decide whether the presented word has been studied or not. Response time was limited to 3000 ms (Fig. 1), after which a resting stimulus consisting of five hashtags (#####) became visible (for 3000 ms). Participants were asked to decide as fast and accurate as possible and were told that they will receive feedback about their amount of correct responses after the experiment.

4.4. Electroencephalogram (EEG)

Electroencephalogram (EEG) was measured by Neurofax Electroencephalograph (Model EEG-1100G, Nihon Koden) and recorded from 32 electrodes all over the scalp, conforming to the extended international 10-20 positioning system and containing 29 active electrodes (Fig. 5), two reference electrodes (A3/A4) and one ground electrode (FPZ). The 29 active electrodes consisted of three midline electrodes (FZ, CZ, PZ) and 13 lateral pairs of electrodes (FP1/2, F7/8, F3/4, FT9/10, FC5/6, FC1/2, T7/8, C3/4, CP5/6, CP1/2, P7/8, P3/4 and O1/2). Two vertical and two horizontal Electrooculogram electrodes (EOG) were recorded to identify blink artifacts. The bipolar montages were placed over and under the right eye and at the outer canthi of each eye. Impedances of the EEG electrodes were kept below 5 kΩ and impedances of the EOG electrodes below 20 kΩ. EEG data was sampled at a rate of 250 Hz, band-pass filtered between 0.1 and 30 Hz and contained a Notch-filter (50 Hz). To get a satisfactory signal-to-noise ratio for each participant, movement and drift artifacts were rejected via individual raw data inspection. Independent Component Analysis (ICA, e.g. Onton et al., 2006) served to correct blink artifacts. Stimulus-locked ERP waveforms were averaged from correct, artifact-reduced trials. Mean number of used trials for ERP averages were 23.48 (SD=5.71) for the old/few condition, 25.00 (SD=5.09) for the old/many condition, 27.00 (SD=5.05) for the new/few condition and 26.10 (SD=5.64) for the new/many condition. Stimulus-locked ERP time windows contained a 200 ms pre-stimulus baseline and continued for 800 ms after stimulus onset. The segments were baseline corrected. EEG-data were analyzed by Brain Vision Analyzer 2.0 (Brain Products GmbH).

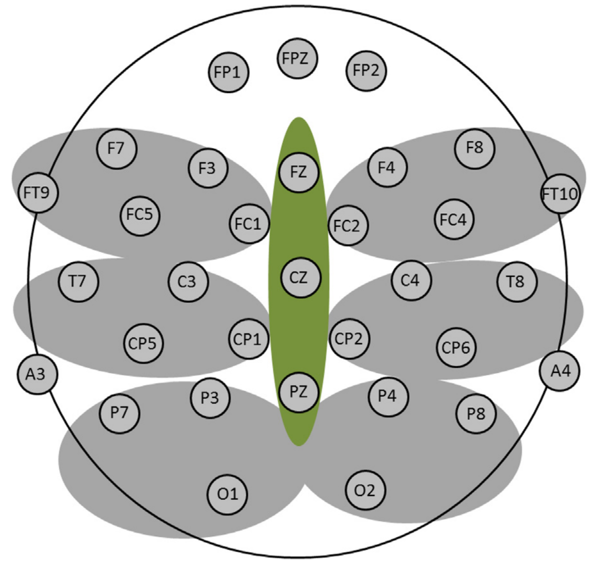

Fig. 5 – Schema used for the electrode positions and the seven topographical clusters. The green area demonstrates the cluster for the midline analysis. The gray areas represent the cluster for the lateral analyses, divided by the laterality levels left and right and the anteriority levels anterior, central and posterior.

Subject averages were computed for all four experimental conditions. To test ERP effects, amplitude values were averaged in two different time windows corresponding to the N400 (320–500) and to the P200 (150–215 ms). Estimates of the ERP were obtained in seven topographical clusters by averaging across corresponding electrodes (Fig. 5). There was one midline cluster (FZ, CZ and PZ). The other six clusters were a combination of the laterality levels left and right and the anteriority levels anterior, central and posterior and contained the following electrodes: anterior-right (F7, F3, FT9, FC5, FC1), anterior-left (F8, F4, FT10, FC6, FC2), central-right (T7, C3, CP1, CP5), central-left (T8, C4, CP2, CP6), posterior-right (P7, P3, O1) and posterior left (P8, P4, O2).

For each time window, there was one 2×2 repeated measures ANOVA with the factors oldness (old vs. new) and number of associations (large vs. small) analyzing the activity in the midline region. Furthermore, one $2 \times 2 \times 2 \times 3$ repeated measures ANOVA with the factors oldness, number of associations, laterality (left vs. right) and anteriority (anterior vs. central vs. posterior) was analyzed for the lateral sites for each time window. For all ANOVAs with more than one degree of freedom, the Greenhouse-Geisser correction (GG, Greenhouse and Geisser, 1959) was applied, when necessary. We will only report significant main effects of the experimental factors oldness and number of associations as well as significant interactions of topographic factors with at least one experimental factor. We will not report purely topographic effects. To compensate for the problem of alpha inflation in a number of n post-hoc tests, we performed Sidak adjustment (Sidak, 1967). Therefore, we report post-hoc tests to be significant only, when they cross a statistical threshold of $p' = 1-(1-0.05)^{(1/m)}$ (m = number of comparisons, p' = Sidak corrected critical p-value). We don't report Sidak corrected p-values, when the testwise p-values already lie above.05.

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