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Cognitive control influences the use of meaning relations during spoken sentence comprehension

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Abstract

The aim of this study was to investigate individual differences in the influence of lexical association on word recognition during auditory sentence processing. Lexical associations among individual words (e.g. salt and pepper) represent one type of semantic information that is available during the processing of words in context. We predicted that individuals would vary in their sensitivity to this type of local context as a function of suppression ability and working-memory capacity. Lexical association was manipulated in auditory sentence contexts, and multiple regression analyses were employed to examine the relation between individuals' brain responses to meaning relations in sentences and measures of working-memory capacity, cognitive control and vocabulary. Lexical association influenced the processing of words that were embedded in sentences and also showed a great deal of individual variability. Specifically, suppression ability emerged as a significant predictor of sensitivity to lexical association, such that individuals who performed poorly on our measure of suppression ability (the Stroop task), compared to those who performed well, showed larger N400 effects of lexical association.

Keywords

N400; Lexical association; Individual differences; Cognitive control

1. Introduction

Individuals vary widely in their use of semantic and syntactic information during sentence and discourse processing. Individual differences in reading skill have been attributed to a number of factors, including word-decoding ability, working-memory capacity, suppression ability, print exposure and background knowledge (e.g. Long, Johns, & Morris, 2006). Although few studies have investigated individual variation during listening comprehension, recent work suggests a link between working-memory capacity and differences in processing spoken language (e.g. Nakano, Saron, & Swaab, 2010). Our goal in the current study was to investigate the extent to which individual differences in working-memory capacity, suppression ability, and vocabulary influence the online processing of lexical associations in spoken sentences. In the following section, we briefly introduce previous studies that highlight the importance of lexical association during sentence processing. We

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then review evidence showing that individual variation in working-memory capacity and cognitive-control ability may influence the processing of meaning relations among words in sentences.

1.1. Lexical Associations as a source of information in context

An important question in the study of human language concerns how meaning is constructed from incoming input during comprehension. Word-level meanings are combined to generate sentence-level meaning, and sentence-level meanings are combined to create a meaningful discourse representation. Although the construction of meaning can be described in this hierarchical fashion, real-time language comprehension does not proceed in such a linear manner. Rather, every incoming word is interpreted in light of its preceding context. The context includes the meanings of the immediately preceding words, the larger message-level meaning, and background context, such as knowledge about a particular speaker. The overall, message-level context exerts a powerful and immediate influence on the processing of incoming words (e.g., Boudewyn, Gordon, Long, Polse, & Swaab, 2012; Camblin, Gordon, & Swaab, 2007; Federmeier & Kutas, 1999; van Berkum Hagoort & Brown, 1999; van Berkum, Brown, Hagoort, & Zwitterlood, 2003). Recent studies have shown that the global context can override and modulate sensitivity to wordlevel factors, such as animacy violation (Filik & Leothold, 2008; Nieuwland & van Berkum, 2006). Although message-level context is a powerful source of meaning during comprehension, wordlevel context, such as semantic relations among words, is also a source of knowledge that is available during comprehension.

Evidence for the role of semantic relations in processing upcoming words comes from studies showing associative priming effects. Associative priming refers to a processing benefit for a target word when it is preceded by an associatively related prime word (e.g. a benefit for pepper after seeing or reading *salt*). This type of association leads to robust and reliable facilitation for word pairs presented in isolation or as lists (e.g. Andruski, Blumstein, & Burton, 1994; Bölte & Coenen, 2002; Marslen-Wilson & Zwitterlood, 1989; Swinney, Onifer, Prather, & Hirshkowitz, 1979; Williams, 1988). For words in isolation, associative priming is manifested by decreased lexical decision times (Andruski et al., 1994; Bölte & Coenen, 2002; Swinney et al., 1979), and reduced N400 amplitudes (Domalski, Smith, & Halgren, 1991; Holcomb, Anderson, & Grainger, 2005; Joyce, Paller, Schwartz, & Kutas, 1999; Rugg, Doyle, & Melan, 1993) for related compared to unrelated target words. However, effects of lexical association for words in sentence contexts have not been consistently observed. In some studies, lexical priming effects are found (Camblin et al., 2007; Coulson, Federmeier, Van Petten, & Kutas, 2005; Hoeks, Stowe, & Doedens, 2004; Van Petten, 1993), whereas, in others, they are not observed (Traxler, Williams, Blozis, & Morris, 2000). In many cases, lexical association effects have been found only under special circumstances, such as when primes and targets appear in the same clause (Carrol & Slowiaczek, 1986), when primes and targets are congruent with the sentence-level meaning (Morris, 1994), when the prime word is in linguistic focus (Morris & Folk, 1998), for words in incongruent sentences (Coulson et al., 2005), and in low-constraint sentences (Hoeks et al., 2004). Still, some studies have found lexical association effects for words embedded in sentence or discourse contexts (Boudewyn et al., 2012; Camblin, Gordon, Swaab, 2007). In

sum, the overall picture based on studies of lexical association in context suggests that word-level associations make a small contribution to language comprehension under normal conditions. In other words, it is reasonable to conclude, based on associative priming studies, that word-level associations are a weak source of information when there is a larger message-level context available.

Other recent work, however, has shown that lexical association can exert an influence during sentence processing (Kuperberg, Sitnikova, Caplan, & Holcomb, 2003; Federmeier & Kutas, 1999; Kuperberg, 2007). For example, Kuperberg et al. (2003) published a study showing an unexpected P600 effect to grammatical sentences containing semantic violations, such as in the following example:

1. For breakfast the boys would only eat toast and jam.
2. For breakfast the eggs would only eat toast and jam.

The above example contains no particularly difficult syntactic structure. However, a larger P600 amplitude was found to critical words like (*eat*) in (1) compared to (2). The P600 is a relatively late (500–700 ms following word onset) positive deflection normally elicited by syntactic errors (e.g. Osterhout & Mobley, 1995) or syntactically complex sentences (e.g. Kaan, Harris, Gibson, & Holcomb, 2000; Kaan & Swaab, 2003). Typically, semantic violations, as in (2), would produce an N400 effect. The N400 is a negative-deflecting ERP that is sensitive to semantic aspects of input. Its amplitude is modulated by semantic relatedness (Domalski, Smith, & Halgren, 1991; Holcomb, Anderson, & Grainger, 2005; Joyce, Paller, Schwartz, & Kutas, 1999; Rugg et al., 1993), and by congruence and predictability in context (Kutas & Hillyard, 1984; van Petten, 1993; Federmeier & Kutas, 1999; van Berkum et al., 1999; for a review, see Swaab, Ledoux, Camblin, & Boudewyn, 2011, chap. 15). Similar “semantic P600” effects have been reported in several other studies (e.g. Kuperberg, Sitnikova, Caplan, & Holcomb, 2006; Kolk, Chwilla, van Herten, & Oor, 2003; Kim & Osterhout, 2005; Nakano, Saron, & Swaab, 2010). Although lexical association is not the only manipulation that produces a semantic P600 effect (see Kuperberg, 2007 for a review), findings such as those described above do suggest that word-level meaning relations play a significant role during language comprehension. Therefore, there is good reason to assume that word-level meaning associations can contribute to the processing of words in context. However, it is important to note that there are many factors that determine whether word-level factors influence the semantic processing of incoming linguistic input, including speed of presentation (Camblin, Ledoux, Boudewyn, Gordon, & Swaab, 2007), working memory capacity (Nakano, Saron, & Swaab, 2010), pragmatic factors (Nieuwland & van Berkum, 2008), and other contextual factors, as noted above (Carrol & Slowiczek, 1986; Coulson et al., 2005; Morris, 1994; Morris & Folk, 1998).

1.2. Individual differences in cognitive capacities affect processing of lexical associations?

An important goal of this paper is to investigate the extent to which individuals vary in their sensitivity to lexical association during sentence processing, as a function of differences in working-memory capacity and cognitive-control ability. As noted above, research suggests that word-level association has a weak influence on the processing of incoming words when

a rich context is available. It is only when context is negligible that the effects of lexical associations among individual words become robust, as in word-pair priming paradigms.

This account of the role of context in modulating the influence of lexical association during discourse processing suggests that message-level context will diminish the lexical association effect only when individuals are able to maintain information about the discourse context in memory during comprehension. Previous research has shown substantial individual differences in readers' ability to maintain and use contextual information as they process sentences (e.g. Long & Chong, 2001; Long, Oppy, & Seely, 1997; Long, Prat, Johns, Morris, & Jonathan, 2008). Individuals who are unable to capitalize on the global message may, as a result, be more sensitive to local context, such as word-level association. We propose that variability in working-memory capacity and suppression ability are likely to influence the effect of word-level association during spoken sentence processing.

1.3. Working-memory capacity

Working memory has been proposed to influence sentence processing in two main ways: by placing limits on storage and computational capacity during language processing (e.g. Just & Carpenter, 1992; Waters & Caplan, 1996), and by varying in efficiency and capacity as a function of experience with language (e.g. MacDonald & Christiansen, 2002). Just and Carpenter (1992) have proposed a capacity theory in which a limited-capacity resource pool underlies language comprehension; individual differences in capacity can explain various differences in sentence processing. Specifically, complex syntactic structures that are computationally demanding leave fewer resources available for the maintenance of sentence context; low working-memory capacity is then expected to influence an individual's ability to maintain contextual information during processing. Another prominent framework is the Separate Sentence Interpretation Resource (SSIR) theory proposed by Caplan and Waters (1999). According to SSIR, there are two separate WM resource pools: one is used during initial syntactic structure-building and one is more general and is tapped during sentence comprehension when an additional task is required (i.e. maintain a verbal load). Only the more general resource is proposed to vary in capacity among individuals (Waters & Caplan, 1996). In contrast to these two models, MacDonald and Christiansen (2002) have proposed a model attributing variability in working-memory "capacity" to individual differences in experience and biological factors (e.g. the quality of phonological representations). By this account, capacity arises from the system as a whole, based on experience. Therefore, individual differences in sentence processing are attributed to variation in skill and experience (MacDonald & Christiansen, 2002).

Studies of the relation between individual differences in working-memory capacity and sentence processing have most often relied on studies of how readers process syntactically complex or ambiguous sentences (e.g. Clifton et al., 2003; Just & Carpenter, 1992). Many studies have found a link between working-memory capacity and syntactic processing ability (Just & Carpenter, 1992; but see Traxler, Williams, Blozis, & Morris, 2005), sensitivity to animacy information during on-line thematic integration in spoken sentences (Nakano, Saron, & Swaab, 2010), thematic relatedness among sentences in discourse

(Cantor & Engle, 1993), sensitivity to word-level association and sentential constraint (Van Petten, Weckerly, McIsaac, & Kutas, 1997), and the ability to recover from unexpected words in discourse (Otten & van Berkum, 2009). Of particular interest here is an ERP study by Van Petten et al. (1997), in which participants received syntactically unambiguous sentences containing associated or unassociated word pairs; sentence congruence was manipulated, with sentences either being congruent or anomalous. The results showed that low working-memory capacity participants were less sensitive to sentence congruity than those with medium or high working-memory spans, as only medium and high working-memory capacity groups showed an N400 effect for the comparison between congruent and anomalous sentences that contained no associations (Van Petten et al., 1997). In contrast, all working-memory capacity groups showed an N400 effect of lexical association, and an N400 effect of sentence congruence for sentences that did contain associations.

Still, relatively little is known about the influence of working-memory capacity on the processing of syntactically simple spoken sentences, compared to structurally complex or ambiguous written sentences. As noted by Nakano, Saron, and Swaab (2010), this is likely because the processing of simple structures is assumed to place minimal demands on working memory. Even so, the relation between working memory and sentence processing is a complex one, and there are some studies that have shown individual differences in the influence of simple sentence context on incoming words as a function of working-memory capacity (Nakano et al., 2010; Van Petten et al., 1997).

1.4. Cognitive control ability

Cognitive control ability also appears to be critical in successful sentence and discourse processing. The term “cognitive control” is difficult to define, as it encompasses a wide range of domain-general functions, including conflict detection and resolution, context-maintenance, and inhibition. It is important to note that the functions subsumed under the term cognitive control may not be separable from those that underlie the construct of working memory. Indeed, several studies have found links between performance on working-memory tasks and performance on executive attention tasks (see Engle, 2002, for a review). Although there is some overlap in the cognitive processes that these tasks are intended to tap, we chose to include separate measures of working-memory capacity and of cognitive control in the current study in order to assess the independent contributions of the two constructs on individual differences in sensitivity to lexical association during sentence processing. Particularly relevant for the current study are control functions related to the suppression of irrelevant information and the maintenance of context-relevant information.

Suppression ability has been argued to be crucial to successful and efficient language comprehension, according to a prominent theory of discourse comprehension, the Structure-Building Framework (Gernsbacher, 1990, 1997; Gernsbacher & Faust, 1991). This model emphasizes the need to suppress context-irrelevant information during comprehension in order to efficiently construct a message-level representation (Gernsbacher, 1990, 1997; Gernsbacher & Faust, 1991). Word-level meaning relations are a source of information that may or may not be relevant to the message-level meaning, as is the case with lexical associates of the context-inappropriate meaning of ambiguous words. Importantly,

individuals vary in their ability to suppress context-irrelevant information: Gernsbacher and colleagues have found that both skilled and less skilled readers successfully select test words relating to the context-appropriate meaning of an ambiguous word (e.g. *garden* after *He dug with the spade*), but less skilled readers are slower than skilled readers at rejecting test words that are related to the context-inappropriate meaning (e.g. *ace* after *He dug with the spade*) (Gernsbacher, Varner, & Faust, 1990, Experiment 4). Similarly, Gernsbacher and Faust (Experiment 4, 1991) found that less skilled readers showed greater facilitation than did skilled readers for context-appropriate meanings following biased contexts (e.g. *garden* after *He dug with the spade*) compared to neutral contexts (*garden* after *He picked up the spade*). This pattern of results suggests that less-skilled readers are able to successfully and efficiently enhance relevant information, but are impaired at suppressing irrelevant information during comprehension.

1.5. Predictions for the current study

The goal of the current study was to investigate individual differences in the online processing of lexical associations in sentence contexts, using ERPs. Meaning relations among words are a rich source of information for recognizing words in pairs or lists, but lexical associations may be a weak source of information compared to the information that is provided in a rich messagelevel context. Variation in the ability to represent, maintain and rely on context may influence priming effects for words in sentences. Here we focus on the relation between sensitivity to local wordlevel association and working-memory span, cognitive control and overall verbal ability. These particular characteristics were selected because they are among those with the greatest correlation with reading skill, and also feature prominently in theoretical accounts of individual differences in comprehension (Long, Johns, & Morris, 2006). We used multiple regression to assess the influence of these characteristics on the amplitude of the N400 effect.

Across all participants, we predicted a main effect of lexical association in the typical 300–500 ms, N400 time window. This would be consistent with our previous findings of ERP effects of lexical association when word pairs were embedded in context (Camblin, Gordon, & Swaab, 2007; Boudewyn et al., in press). Furthermore, we predicted that individuals would vary in their sensitivity to lexical association, varying in the amplitude of the lexical association effect. ERP effects naturally vary in amplitude from person to person, but this fluctuation may be informative about individual differences in processing if it can be linked to variability in working-memory capacity and cognitive control.

Van Petten et al. (1997) found lexical association effects in the N400 time window for both high and low working-memory capacity individuals. However, individuals with low working-memory span were less sensitive to sentential context congruity than those with high working-memory span. Following from this, we predicted that low working-memory capacity individuals would be more sensitive to the local word-level context as a function of decreased sensitivity to the overall sentential context. In other words, low working-memory capacity may lead to a decrease in sensitivity to sentence-level context, resulting in an enhanced word-level association effect if a weaker sentence-context representation renders the associative relation between prime and target salient. Therefore, low working-memory

capacity individuals were predicted to show a larger association effect than high working-memory capacity individuals.

In addition, we expected cognitive control ability to influence sensitivity to local lexical association. Control and suppression of irrelevant information are important aspects of language comprehension, and as noted above, skilled readers appear to have greater suppression ability than less skilled readers (e.g. Gernsbacher, Varner, & Faust, 1990). In the context of the current paradigm, which involves listening to spoken sentences for comprehension, we argue that lexical association is not the most relevant source of information in trying to construct the meaning of a sentence as a whole. In other words, when the goal is to understand a sentence, the presence of word associations is somewhat irrelevant, just as context-inappropriate meanings of ambiguous words would be (although perhaps not to the same extent). It may therefore be important to suppress lexical associates during sentence comprehension. This is not to say that lexical associations may be completely inhibited given good suppression ability, however poor suppression ability may lead to larger amplitude association effects. Therefore, cognitive control ability in the current experiment may influence sensitivity to local lexical association, such that low control participants show an over-reliance on word-level relations. Specifically, this would manifest as a larger N400 effect in low-control than in high-control participants.

To test the relation between variability in working-memory capacity, cognitive control, and sensitivity to lexical association in meaningful sentence contexts, we collected three behavioral measures (one WM measure, one cognitive control measure, and one verbal skill measure) for each participant who completed the ERP portion of the experiment. In the ERP portion of the experiment, we manipulated lexical association in auditory sentence contexts. We then used multiple regression to investigate the relation between the behavioral and ERP data. Multiple regression analysis allowed us to partial out the unique contribution of each behavioral measure in predicting the dependent measure (ERP values). It is worth noting that the current study is one of a very limited number of studies that have adopted a multiple regression approach to studying individual differences using ERPs. This is because of the poor signal-to-noise ratio (S/N) of individual ERP effects. Typically, ERP waveforms are averaged across all trials of a condition within participants and then across all participants. The relation between the S/N and the number of trials is such that, in order to double the S/N, one must quadruple the number of trials (Luck, 2005). Further, in studies of language, the total number of trials per participant is constrained by how long the experimental materials take to present to participants and by the need to avoid repetition of the same stimuli (Swaab et al., in press). In practice, this means that the number of trials per condition, per participant is usually between 25 and 40, making the S/N for single-subject ERP data in language studies rather low. These difficulties account for the paucity of individual difference studies of language, particularly those using methods reliant on single-subject values, such as multiple regression analyses. Although difficult, it is possible to apply these methods by increasing the number of participants (e.g. Dambacher, Kliegl, Hofmann, & Jacobs, 2006; Laszlo & Federmeier, 2011). The current study is one of only a handful of ERP studies to use this method, and to the best of our knowledge, is the first to do so to study the relation between measures of working memory, cognitive control, verbal skill and online comprehension of spoken language.

2. Methods

Participants

Fifty undergraduates (26 female) from the University of California, Davis gave informed consent before participating in the study. They were compensated with either course credit or at a rate of ten dollars per hour. All were right-handed, native speakers of English, with no reported problems with hearing or reading or neurological/psychiatric disorders. The mean age of participants was 19.77 (range: 18–30).

2.1. Methods: ERP session

2.1.1. Stimuli—Stimuli consisted of single sentences adapted from three-sentence discourse passages that were used in a previous study (Boudewyn et al., in press). Stimuli were identical to the passage-final sentences used in Camblin et al. (2007) and Boudewyn et al. (in press). Sentences contained a critical final word that was either associated or unassociated with a preceding word in the sentence, though the critical word was congruous at the sentence level in each condition, as in Example 1 below.

1. In her haste she forgot to buy the apples^{prime} and oranges^{associated target}/
bread^{unassociated target}.

The mean sentence length was 11.16 words (range 8–17 words). Associated prime-target word pairs were culled from the Edinburgh Associative Thesaurus (Kiss, Armstrong, Milroy & Piper, 1973) and from association pre-tests. All associated word pairs had an association strength of at least 20%, with an average rating of 39.8% (range: 20–90%). Unassociated word pairs were created by using control words that were not associated, or were only mildly associated, with the prime (average association score of 0.2%, range 0–4%). The associated and unassociated target words were matched on word frequency using Francis and Kucera (1982) word counts (associated: $M=83.71$ per million, $SD=136$; unassociated: $M=83.86$ per million, $SD=182$; $t < 1$). Cloze probability for target words in these single-sentence contexts was low, averaging 13.7%. Cloze probability for associated target words averaged 24.9%, which was significantly higher than the average for unassociated target words ($p < 0.001$).

In order to determine whether the difference in cloze probability between the two conditions should be attributed to the presence of the associated prime word or to sentence-level predictability, we conducted an additional cloze probability pre-test for the sentences, cutting off the sentences before the prime instead of the target (e.g. In her haste she forgot to buy the _____). This resulted in an average cloze probability for the target word of 1.7% (2.8% for associated targets, 1% for unassociated targets). The average cloze probability for the prime word was 2.7%. Importantly, this shows that the sentences themselves were not constraining, and that the difference in cloze probability between conditions at the target word can be attributed to the presence of the prime word alone.

Eight sentences were dropped from the original stimulus set because they shared a prime or target word with a different sentence in the set. Thus, 64 sentences in two conditions were divided into two lists with each sentence appearing only once in a list. Each list contained 32

sentences per condition. The lists also contained 40 filler sentences. Twenty of these sentences were congruous and 20 ended with a final word that was anomalous with the preceding sentence context. Filler sentences containing anomalous final words were included so as to provide instances of incongruent sentence endings within the experiment, with the intention of rendering the differences among congruent conditions (associated/unassociated/filler) less noticeable. Lists were divided into four blocks that each contained 16 experimental and 10 filler sentences. Lists 1 and 2 were matched such that a sentence that appeared in associated form on one list appeared in unassociated form on the matched list. Participants heard either list 1 or 2, with presentation order of the lists and blocks counterbalanced across subjects. Ten additional sentences were constructed for a practice session that was run before the presentation of list stimuli. The practice sentences were the same for each subject.

Audio recording of the sentence stimuli was carried out as part of a related experiment (Boudewyn et al., 2012). All sentences and fillers were spoken by a female speaker, with natural inflection and at a natural speaking rate. The sentences were digitally recorded using a Schoeps MK2 microphone and Sound Devices USBPre A/D (44, 100 Hz, 16 bit). Speech onset and offset of each critical word in all conditions were determined by visual inspection of the speech waveform and by listening to the words using speech-editing software (Audacity, by Soundforge). The average duration of the sentences was 3612 ms (ranging from 2116 to 6281 ms), and the average duration of the critical words was 568 ms (ranging from 293 to 861 ms). The duration of the critical words did not differ between conditions ($t < 1$).

2.1.2. Procedure—The ERP session always preceded the behavioral battery in order to minimize participant fatigue during the more demanding ERP portion of the experiment. Participants were informed at the beginning of the ERP session that the experiment was focused on language comprehension. Before beginning the behavioral battery, participants were informed that the battery was not an intelligence test, and not to feel upset if they found some of the tasks to be difficult. During the ERP session, participants were seated in a comfortable chair in an electrically shielded, sound-attenuating booth. The stimuli were presented through Beyer dynamic headphones using Presentation software. The auditory presentation of each sentence began with a white fixation cross at the center of the screen, approximately 100 cm in front of participants. The fixation cross was present from 1500 ms before the onset of the sentences and during presentation of the entire sentence until the offset of the final word. The fixation cross was then replaced by a visually presented true/false question about the preceding sentence. True/False questions were intended to encourage processing of the meaning of the sentence as a whole. For example, following “In her haste she forgot to buy the apples and oranges/bread”, the corresponding true/false question was “She meant to buy apples.” Please see the appendix for additional examples. Participants were asked to respond by pressing one of two buttons on a button box, corresponding to either true or false. The comprehension question remained on the screen until the participant made a response.

Participants were asked to keep their eyes fixated on the white fixation cross and to refrain from blinking or eye-movements as long as it remained on the screen. This was done in

order to minimize movement-related artifacts in the EEG signal. When the fixation cross was replaced by the true/false question, participants were instructed that they could blink and move their eyes freely until they made a response. Condition-specific stimulus codes were sent out at the onset of the critical words and these codes were used for later off-line averaging of the EEG signal.

2.1.3. ERP recording and data reduction—EEG was recorded from 29 tin electrodes, mounted in an elastic cap (Electro-Cap International). Additional electrodes were placed on the outer canthi and below the left eye in order to monitor eye movements and blinks. The right mastoid electrode was used as the recording reference. The left mastoid was also recorded for later off-line algebraic re-referencing. The EEG signal was amplified with band pass cutoffs at 0.1 and 30 Hz, and digitized on-line at a sampling rate of 250 Hz (Neuroscan Synamp I). EEG was digitized continuously along with accompanying stimulus codes used for subsequent averaging. Impedances were kept below 5 k Ω .

Prior to off-line averaging, all single-trial waveforms were screened for amplifier blocking, muscle artifacts, horizontal eye movements and blinks over epochs of 1200 ms, starting 200 ms before the onset of the critical target words. Average ERPs were computed over artifact-free trials in the related and unrelated conditions. All ERPs were filtered off-line with a Gaussian low-pass filter with a 25 Hz half-amplitude cutoff. Statistical analyses were conducted on the filtered data.

2.2. Methods: behavioral battery

2.2.1. Listening Span—The Listening Span task was adapted from Daneman and Carpenter (1980), and consisted of 25 sets of sentences ranging from two sentences per set to six; there were five sets of each set length. Participants were instructed to listen to all sentences within each set for comprehension, and then to indicate whether each sentence was true or false immediately after hearing the whole sentence. In addition, participants were instructed to remember the final words of each sentence in the set, and were asked to recall them in any order after the whole set was presented. There was a 1500 ms pause in between each sentence during which participants made their true/false response. Presentation of sets was random. Each correct response (correct recall of the final words) was scored as one point, for a maximum of 100 points. This task, which was adapted from its visual counterpart (Reading Span), predicts reading comprehension and syntactic parsing abilities, particularly when used in conjunction with other tasks (Waters & Caplan, 2003).

2.2.2. Modified Stroop—The Modified Stroop Task was adapted from that used in Van Veen and Carter (2005), and consisted of visual presentation of color words (blue, green, yellow and red). Words were printed in each of these colors, and participants were instructed to respond to the color of the font and not the word itself; responses were mapped such that a left button press indicated the word was in red or yellow font color, and a right button press indicated that the word was in blue or green font. Trials were either congruent (e.g. “red” in red) (50%), semantically incongruent in that the font color and word were not the same but were mapped onto the same finger (e.g. “red” in yellow) (25%), or response incongruent, in that the font color and word were not the same and additionally were not

mapped onto the same finger (e.g. “red” in green) (25%). There were 124 total words presented in random order per block, and 3 experimental blocks. Each word appeared on the screen for 300 ms, separated by a 2700 ms inter-stimulus interval. This version of the Stroop task was designed to separate conflict at the representational level and conflict at the response level by including semantically incongruent (SI) trials in addition to response incongruent (RI) and congruent trials. RI trials are assumed to reflect both semantic and response conflict, because they involve a mismatch between (1) the font color and the color being named, and (2) the button response required for the font color and the button response that is required for the color being named. An example of an RI trial is the word “red” printed in green font, when red font has been mapped to one button/finger and green font has been mapped to another. In contrast, SI trials are assumed to reflect only semantic conflict because the button response for both the font color and the color being named is the same. An example of an SI trial is “red” printed in yellow font, when both red and yellow fonts are mapped to the same response button/finger (De Houwer, 2003; Van Veen & Carter, 2005).

2.2.3. Nelson–Denny—The Nelson–Denny is a standardized paper and pencil test. Participants were allotted 15 min to complete the vocabulary portion of this test. The Nelson–Denny is an assessment of overall reading skill (Long, Prat, Johns, Morris, & Jonathan, 2008) and, in the case of this experiment, was employed to account for individual variation in the ERP data that may be due to variability in comprehension.

3. Results

3.1. Results: behavioral data

Comprehension questions—On average, participants were highly accurate in answering the true/false comprehension questions that followed each sentence (95%; range: 87–100%).

Listening Span—Listening Span was calculated as the total percent of correctly recalled items (out of a total of 100). The average score was 67.94% (range: 41–86%; SD=11.49).

Modified Stroop—Mean RTs were 604.95 ms, 616.27 ms, and 677.68 ms for congruent (C), semantically incongruent (SI), and response incongruent (RI) words, respectively. Planned contrasts revealed no significant difference between the C and SI conditions ($p=0.31$), but there was a significant difference between the C and RI conditions ($p=0.0008$). Mean accuracy was 95% (C), 95% (SI) and 94% (RI); the difference in accuracy between the C and RI conditions was significant ($p=0.001$). For the purposes of the regression and correlation analyses reported below, a single measure of Stroop Interference was created from the Stroop RT scores. Specifically, for each subject, the average difference between RI and C trials was calculated; the values were then z-transformed.

Nelson–Denny—This was calculated as the percentile rank for the vocabulary section, Form G. The average score was 79.97% (range: 42.5–96.25%; SD=11.61). In the regression and correlation analysis below, this measure is referred to as Vocabulary Table 1.

Correlations between Behavioral Measures—Simple correlation tests revealed no significant correlations between the behavioral measures tested.

3.2. Results: ERP data

The grand average across all participants showed that unassociated targets elicited more negative waveforms than associated targets (Fig. 1). A repeated measures ANOVA was conducted with Association (Associated, Unassociated) and Electrode Site (25 sites) as within-subjects factors, on the mean amplitude in the typical 300–500 ms N400 window. Four frontal electrode sites were excluded from this and all further analyses because of excessive drift (FP1, FP2, F7, F8). The Greenhouse–Geisser correction was applied to all *F* tests with more than one degree of freedom in the numerator. This test showed a main effect of Association ($F(1,49)=30.49$; $p=0.0000$), and a significant Association by Electrode interaction ($F(24, 1176)=2.8$; $p=0.0269$). In order to determine the onset of this effect, repeated measures ANOVAs were performed across overlapping 100 ms epochs between 150 and 800 ms (150–250 ms, 200–300 ms, 250–350 ms, 300–400 ms, 350–450 ms, 400–500 ms, 450–550 ms, 500–600 ms, 650–750 ms, 700–800 ms). Results for these analyses showed significant association effects in all windows; these are reported in Table 2.

Following from the significant Association by Electrode interactions reported in Table 2, additional analyses were conducted over 13 fronto-central, central, central-parietal, and parietal electrode sites (F3, F4, Fz, FC1, FC2, C3, C4, Cz, CP1, CP2, P3, P4, Pz). Results showed a significant main effect of association in the typical 300–500 ms N400 time window ($F(1,49)=29.91$; $p=0.000$); the onset analyses for this subset of electrodes, shown in Table 3, showed significant main effects of association from 150 to 800 ms, with no interactions with electrode.

3.3. Results: regression analyses

3.3.1. Dependent measures—We estimated the N400 effect size for each individual by calculating an area amplitude measure. We first computed a difference waveform for each participant (Unassociated–Associated), and then measured the area under the resulting waveform that fell within the classic 300–500 ms N400 window.

3.3.2. Single regression analyses—Effect Size estimates were calculated for each individual over three posterior electrode sites (P3, P4, Pz). These electrodes were chosen because previous studies have found the N400 to be maximal at these sites (see Swaab et al., 2011 for a review). As can be seen in Fig. 1, the N400 effect was maximal at these sites in the current study as well. In addition, previous ERP studies employing regression analyses have focused on similar subsets of electrode sites (e.g. Dambacher, Kliegl, Hofmann, & Jacobs, 2006; Laszlo & Federmeier, 2011). Single regression correlations on Effect Size showed a significant effect only for Stroop Interference ($r=0.37$ ($r^2=0.119$; $p=0.008$)); all other single regression correlations with Size were not significant.

3.3.3. Multiple regression: effect size—Listening Span, Stroop Interference and Vocabulary were entered into a multiple regression analysis as predictors of effect size. This approach allowed us to assess the unique contribution of each of these measures in

predicting the size of the N400 effect. Of these three predictors, only Stroop Interference reached significance (see Table 4), $r=0.421$ ($r^2=0.177$; $p=0.031$). All other variables were systematically removed from the model, with the pattern remaining the same: only Stroop Interference significantly predicted effect size: $r=0.37$ ($r^2=0.119$; $p=0.008$), such that poor cognitive control was linked to a larger N400 effect in the classic time window. Fig. 2 depicts the relation between effect size and Stroop Interference. In order to determine whether this result can be attributed to (1) a greater reduction in the N400 to associated words for low control individuals than high control individuals, or (2) a higher amplitude N400 to unassociated words for high control individuals than low control individuals, the size of the N400 for each condition separately was calculated as described above. The dataset was then split into two groups: poor Stroop performance ($n=20$) and good Stroop performance ($n=20$). The poor Stroop performance group was the bottom 40% of Stroop Interference performance, whereas the good Stroop performance group was the top 40%; individuals performing in the middle 10% ($n=5$) were not included in this analysis. As can be seen in Fig. 3, the two groups did not significantly differ in the size of the N400 waveform in response to unassociated words. Instead, the N400 response in the poor Stroop performance group was significantly more reduced than in the good Stroop performance group for associated words ($p=0.04$).

4. Discussion

In accordance with our predictions, we found a robust and long-lasting effect of association across all participants, such that amplitude was significantly more negative in response to unassociated target words than their associated counterparts. This effect was significant from 150 ms through 800 ms. This was not surprising, given that previous studies have also shown effects of lexical association in sentence and discourse contexts using similar materials (Boudewyn et al., 2012; Camblin, Gordon, & Swaab, 2007). However, we also found substantial individual variation in the size of the effect.

The only measure to emerge as a significant predictor of the size of the lexical association effect was Stroop Interference. The Stroop task capitalizes on the automaticity of reading by presenting color words (e.g. red) in congruent and incongruent fonts (e.g. red and blue, respectively) and asking participants to respond to the font color in which the words are printed. In order to succeed in this task, participants must overcome the inclination to respond to the word, thus tapping into cognitive control mechanisms, and in particular, providing an index of suppression ability (Cohen, Dunbar & McClelland, 1990; MacLeod, 1991). In the current study, the size of the effect in the traditional N400 time window was significantly related to Stroop Interference, such that individuals who scored poorly on the Stroop task had larger N400 effects of association. This result is consistent with our predictions, in that individuals who performed poorly on the Stroop task were particularly sensitive to local lexical association in the typical N400 window.

This pattern indicates that general suppression ability contributes to individual differences in sensitivity to word-level context (associations) during simple sentence comprehension. The goal of sentence comprehension, irrespective of suppression ability, is to understand the sentence as a whole, which involves building and maintaining a representation of the

sentence meaning over time, and likely involves the generation of expectations about upcoming input based on the sentence context. As mentioned in Section 1, associative relations between individual words are not particularly important or even necessarily helpful in determining the meaning of the larger sentence context. Our results suggest that high control individuals more effectively suppress the associative relation between the prime and target words upon encountering the target, thereby showing a smaller N400 effect of association. In contrast, low control individuals are less effective at suppressing the local meaning relation between prime and target during early stages of processing, leading to a larger N400 effect of association.

Importantly, we interpret the difference in the N400 between associated and unassociated conditions as resulting primarily from the presence of the associated prime word, and not from message-level predictability. We favor this interpretation for two reasons, although it is of course very difficult to completely exclude the possibility of a contribution from message-level meaning. First, although there was a difference in cloze probability between the two conditions, indicating that the associated word was more predictable than the unassociated word, this difference disappeared when the primes were removed from the sentence contexts. This shows that the difference in cloze probability between conditions can be attributed to the presence of the associated prime alone, rather than to message-level predictability. Second, as can be seen in Fig. 3, both low and high control individuals had a similar N400 response to unassociated words, but the reduction of the N400 to associated words was greater in the low control group than in the high control group. This pattern rules out the possibility that the effects reported above were driven by difficulty on the part of low control individuals in integrating unexpected endings based on message-level predictability. If this was the case, the low control group should have shown a larger N400 response to the unassociated words than the high control group. Since the difference between groups is, instead, in the associated condition, this suggests that low control individuals were more sensitive to the presence of a lexical association in the context immediately preceding the critical word, which may be accounted for by less effective suppression of the association.

Suppression of irrelevant information has long been known to be important during language comprehension (Gernsbacher, 1990, 1997; Gernsbacher & Faust, 1991), and as noted above, associations among individual words in a sentence are not necessarily the most relevant source of information (compared to the larger meaning) if the goal is to understand the sentence. Therefore, suppression of this information may be typical during sentence processing, with individual variation depending on suppression ability as well as other factors. Indeed, previous work has argued that reduced or null effects of associative priming may be best described in terms of suppression rather than the absence of semantic activation (Marí-Beffa, Fuentes, Catena & Houghton, 2000). Norris and colleagues argue that, in sentence contexts, lexical associates of prime words may be activated but are inhibited, because the task at hand is to understand the sentence as a whole, not to focus on individual words (Norris, Cutler, McQueen & Butterfield, 2006). This has implications for the current paradigm, in which the task was to listen to the sentences for comprehension. The sentences were short and were not particularly rich in semantic content, but provided a more extensive context than would individual word primes. Perhaps it is not surprising that we found an overall effect of association. However, it seems that the local context of the associated prime

words was particularly salient for low control individuals, because those participants were less able to suppress semantic activation or expectancies for upcoming input than high control individuals. As mentioned above, the results of our analyses of the size of the N400 effect showed that suppression ability alone was predictive of the size of the response to lexical association during the processing of minimal sentence context. This is particularly interesting given that previous studies have linked low working-memory capacity with a decrease in sensitivity to sentence-level context (e.g. Nakano et al., 2010; Van Petten et al., 1997), which may lead to a greater reliance on word-level information during sentence processing. However, it may be the case that working-memory span failed to emerge as a significant predictor of the size of the association effect because the simple, short sentence contexts used in the current study were not particularly demanding of WM resources, averaging only 11 words per sentence. In contrast, sentences in the Van Petten et al. (1997) study were longer (average of 14 words), and therefore may have been more complex, and/or richer in semantic information, leading to a greater reliance on WM resources during the processing of these sentences.

Lastly, although the Nelson–Denny vocabulary test has been shown to be an excellent predictor of reading skill (Long & Chong, 2001; Long, Prat, Johns, Morris, & Jonathan, 2008), it did not emerge as a significant predictor of the lexical association effect in the current study. It is possible to interpret this result such that vocabulary is not as important a predictor of spoken language comprehension as of text comprehension. However, it is more likely that the Nelson–Denny test failed to predict the ERP response in the current study because all of the sentences used in our study were simple, and contained common, high-frequency words. Therefore, individual differences in vocabulary were unlikely to contribute to variability in the processing of our sentences.

Our results are relevant to previous studies of lexical association in sentence contexts, which, as mentioned in Section 1, have yielded mixed results. Several linguistic factors have been shown to influence the effect of associations among words in sentences. For example, one important factor is the message-level meaning of the sentence in which a target word is embedded. Highly constraining sentential context may interact with and partially obscure the influence of lexical associations (Hoeks, Stowe, & Doedens, 2004); indeed, Coulson et al. (2005) found facilitation for lexically associated words in incongruent but not congruent sentences. However, lexical association effects have been observed in *both* congruent and incongruent discourse contexts in the visual modality (Camblin et al., 2007) and the auditory modality (Boudewyn et al., in press). The pattern of results for related studies using eye-tracking is different, on the other hand: Morris (1994) found lexical association effects for words that were congruent but not incongruent in their sentence context, whereas Traxler et al. (2000) did not find such effects regardless of whether or not the critical words were consistent in the sentence. The strength of the lexical associations in the stimulus materials may have contributed to this contradictory pattern across studies. In the case of Morris (1994), the degree of association between the prime words (e.g. *barber* and *trimmed*) and the target word (*mustache*) was moderate. It is possible that this may have contributed to the lack of association effects for incongruent sentences. In addition, this study did not include an “unassociated” condition, but rather varied the sentence-level meaning while keeping the

prime and target words constant. However, Traxler et al. (2000) manipulated both sentence-level meaning (overall plausibility) and relatedness (lumberjack-*axe* vs. man-*axe*) and did not find lexical association effects with eye-tracking methods. Our results suggest that, in addition to these linguistic variables, individual reader/listener characteristics are a source of variability in the influence of association during normal language comprehension of words in sentences. In particular, these individual meaning relations are salient and have an immediate and robust influence on processing for low control listeners.

Our results are also relevant to a recent model of language processing proposed by Kuperberg (2007). According to her model, two processing streams contribute to language comprehension: a semantic memory-based stream and a combinatorial stream. The combinatorial stream computes meaning based on linguistic constraints, such as morphosyntactic information. Of particular relevance to the current study is the semantic memory-based stream. The semantic stream computes meanings based on semantic features and relations among words in a sentence, and processing difficulties in this stream are reflected in the N400 component (Kuperberg, 2007). Further, the balance and interaction between the two streams require cognitive control resources. Impaired control results in an imbalance between the semantic memory-based stream and the combinatorial stream, providing a possible explanation for language difficulties in disorders such as schizophrenia and may influence processing even in healthy individuals (Kuperberg, 2007). This suggestion is consistent with the results of the current study, as low control individuals showed particularly robust N400 effects of lexical association.

5. Conclusions

Our results show that listeners are sensitive to the presence of lexical associations that are embedded in spoken sentences; however, they vary in the relative weight placed on this type of semantic cue during processing. Individuals with poor suppression ability are influenced by associative relations in the local sentence context to a greater degree than individuals with good suppression ability. Lexical association is one of many sources of semantic information available to the language processor during sentence comprehension, and our results suggest that individuals vary in their reliance on this kind of local context as a function of suppression ability.

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Appendix

Example sentences showing the associated/unassociated conditions. For clarification, the primes are shown in italics and target words are capitalized. This is for illustration purposes only; during the experiment these words were not specifically emphasized.

1. In her haste she forgot to buy the *apples* and ORANGES/BREAD.

True or False: She meant to buy apples

2. They stocked plenty of *gin* and TONIC/VODKA.
True or False: They did not stock gin.
3. The kids were so proud of their creation made of *macaroni* and CHEESE/SAUCE.
True or False: The kids made a meal.
4. She couldn't stop scratching her *arms* and LEGS/NOSE.
True or False: Her arms were itching.
5. She looked forward to the *summer* and WINTER/CHRISTMAS.
True or False: She was excited for the springtime.
6. The story was definitely appreciated by *adults* and CHILDREN/TODDLERS.
True or False: The story was not suitable for kids.
7. He needs to stay away from the *sawdust* and WOOD/TOOLS.
True or False: He shouldn't get close to the sawdust.
8. Unfortunately he ran out of *bread* and BUTTER/JAM.
True or False: He had no more spaghetti.
9. She purchased some nice *pots* and PANS/DISHES.
True or False: She bought patio furniture.
10. He was not prepared for the *fame* and FORTUNE/PRAISE.
True or False: His fame was unexpected.

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Fig. 1.

Effects of lexical association, across all 50 participants for representative frontal, central and posterior midline electrode sites. Displayed on the right is a topographic map showing the scalp distribution of the N400 effect (unrelated-related) in the 300–500 ms time window. Electrodes P3, Pz, and P4 are highlighted in yellow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 2.

Single regression correlations between Stroop Interference and Effect Size. On the Y-axis is Effect Size; on the X-axis is Stroop Interference. High values of Stroop Interference indicate poor performance, while low values indicate good performance.

Fig. 3. Effect Size for Associated and Unassociated conditions, by Stroop Interference performance. On the X-axis is Effect Size. $*p < 0.05$.

Table 1

Summary of behavioral data measures.

Measure	Average	Standard deviation
Listening Span	67.94%	11.49
Stroop Interference	72.73 (raw scores)	48.11 (raw scores)
Vocabulary	79.97%	11.61

Table 2

Results of lexical association from repeated measures ANOVAs across 25 electrodes, across all 50 participants. The degrees of freedom for effects of Association are (1,49) and for Association by Electrode interactions are (24,1176).

Epoch (ms)	<u>Association</u>		<u>Association × electrode</u>	
	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>
150–250	5.08	0.0288	3.53	0.0084
200–300	13.46	0.0006	3.66	0.0067
250–350	21.45	0.0000	3.4	0.0102
300–400	29.32	0.0000	3.19	0.0144
350–450	29.9	0.0000	2.32	0.0582
400–500	18.48	0.0001	2.28	0.0475
450–550	18.73	0.0001	2.6	0.0371
500–600	21.72	0.0000	2.49	0.0488
550–650	18.9	0.0001	2.36	0.0548
600–700	13.05	0.0007	2.77	0.0188
650–750	7.09	0.0105	2.21	0.0545
700–800	4.02	0.0504	1.5	0.2046

Table 3

Results of lexical association from repeated measures ANOVAs across 13 electrodes (F3, F4, Fz, FC1, FC2, C3, C4, Cz, CP1, CP2, P3, P4, Pz), across all 50 participants. The degrees of freedom for all *F* values are (1, 49).

Epoch (ms)	Association	
	<i>F</i>	<i>p</i>
150–250	6.34	0.0151
200–300	15.19	0.0003
250–350	24.04	0.0000
300–400	31.13	0.0000
350–450	27.77	0.0000
400–500	17.79	0.0001
450–550	18.61	0.0001
500–600	21.43	0.0000
550–650	18.71	0.0001
600–700	13.68	0.0005
650–750	7.79	0.0075
700–800	4.52	0.0387

Table 4

Multiple regression analysis of Lexical Association Effect Size (3 predictors) showing unstandardized (b) and standardized (β) partial coefficients, and probability levels (p).

Predictor	b	β	p
Constant	794.874		
Listening Span	1.095	0.046	0.738
Stroop Interference	108.734	0.402	0.005
Vocabulary	-2.301	-0.098	0.472