Neuropsychologia 133 (2019) 107127

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Understanding associative vs. abstract pictorial relations: An ERP study☆

Leemor Zucker[a,*], Liad Mudrik[a,b]

[a] Sagol School for Neuroscience, Tel-Aviv University, Ramat Aviv, POB 39040, Tel Aviv, 69978, Israel
[b] School of Psychological Sciences, Tel-Aviv University, Ramat Aviv, POB 39040, Tel Aviv, 69978, Israel

ARTICLE INFO

Keywords:
N400
Late negativity
Relational processing
Semantic integration
Expectations mechanisms
Object processing

ABSTRACT

One of the most remarkable human abilities is extracting relations between objects, words or ideas – a process that underlies perception, learning and reasoning. Yet, perhaps due to its complexity, surprisingly little is known about the neural basis of this fundamental ability. Here, we examined EEG waveforms evoked by different types of relations, conveyed by pairs of images. Subjects were presented with the pairs, that were either associatively related, abstractly related or unrelated, and judged if they were related or not. Evidence for a gradual modulation of the amplitude of the N400 and late negativity was found, such that unrelated pairs elicited the most negative amplitude, followed by abstractly-related pairs and lastly associatively-related ones. However, this was confined to first encounter with the pairs, and a different, more dichotomous pattern was observed when the pairs were viewed for the second time. Then, no difference was found between associatively and abstractly related pairs, while both differed from unrelated pairs. Notably, when the pairs were sequentially presented, this pattern was found mostly in right electrodes, while it appeared both in left and right sites during simultaneous presentation of the pairs. This suggests that while two different mechanisms may be involved in generating predictions about an upcoming related/unrelated stimulus, online processing of associative and abstract semantic relations might be mediated by a single mechanism. Our results further support claims that the N400 component indexes multiple cognitive processes that overlap in time, yet not necessarily in neural generators.

1. Introduction

Relational processing – the ability to judge the relations between two separate elements, and to integrate them into a new representation (Goodwin and Johnson-Laird, 2005; Halford et al., 1998; Hummel and Holyoak, 2003; Doumas et al., 2008) - is considered a key feature of higher cognition, fundamental for multiple functions, such as reasoning, planning, language comprehension and acquisition, learning and decision-making. Accordingly, it is held by some to be the main evolutionary step separating humans from other primates (Halford et al., 2010; Vendetti and Bunge, 2014; Gentner, 2010). Indeed, humans are continuously engaged in relation processing, and do so in a seemingly effortless manner; as babies, we pick up associations between words by using analogical-comparison processes like structural alignment, which aid language acquisition (Gentner and Namy, 2006) and general cognitive development (Gentner, 2016). Similarly, we detect and capitalize on associative relations between objects in our environment in an automatic manner, hereby facilitating object recognition and scene comprehension (Bar, 2004).

More formally defined, relational processing is the binding between a relation symbol (or a predicate) and a set of ordered tuples of elements (Halford et al., 2010). To be regarded as a relation, as opposed to an attribute, the tuple should have at least two elements (e.g. PUSH (x,y) or even RELATED(x,y) is a relation, while SMALL (x) is an attribute; Gentner, 1983). A further distinction is typically made between relational processing and mere associations (Keppel and Postman, 1970), that are based on co-occurrences in language (McNamara, 1992; Plaut, 1995), and assumed to reflect word use, rather than word meaning (Thompson-Schill et al., 1998); the latter are held to be supported by spreading activation, being a more reflexive and automatic process (Neely, 1977; Collins and Loftus, 1975; Tversky, 1977). Relational processing, on the other hand, is typically considered to be based on semantics and structure-consistent mappings (Halford et al., 2010), which are more reflective and demanding processes (Gentner, 1983).

Within the realm of relational processes, previous literature has suggested several taxonomies for relation types – based on structure, content, or strength. Structure-wise, relations can be classified based on relation complexity (Kroger et al., 2004), differentiating between first-order and second-order relations, for example. This could take the form of predicates that bind first-order relations into an abstract relational

☆ The authors declare no competing financial interests.

* Corresponding author. School of Psychological Sciences and Sagol School of Neuroscience, Tel Aviv University, Ramat Aviv, POB 39040, Tel Aviv, 69978, Israel.
E-mail address: mudrikli@tauex.tau.ac.il (L. Mudrik).

https://doi.org/10.1016/j.neuropsychologia.2019.107127
Received 13 January 2019; Received in revised form 31 May 2019; Accepted 18 June 2019
Available online 04 July 2019

structure. (e.g., if COLLIDE (x,y) and STRIKE (y,z) are first-order predicates, CAUSE [COLLIDE (x,y), STRIKE (y,z)] is a second-order; Gentner, 1983). Others consider second-order relations to index relations between relations. For example, when subjects compare pairs of words/pictures, and determine if they convey the same or different relations, like BIRD:NEST:BEAR:CAVE, vs. BIRD:NEST:FORK:EAT; (Spellman et al., 2001; see also Cho et al., 2009; Vendetti and Bunge, 2014). A *content-based classification* differentiates relations type based on their meaning (e.g., Vendetti and Bunge, 2014): for example, visuospatial relations (e.g., the spoon is to the right of the cup), numerical relations (e.g., 3 is smaller than 7), temporal relations (e.g., the computer turns on after pushing the button), and semantic relations (e.g., a knife is used to cut bread). Finally, some studies relied on *relation strength*, differentiating between strongly-related and weakly-related pairs of words (e.g., Kutas et al., 1988; see also Lau et al., 2013 for a similar manipulation with sentences) or pictures of objects (e.g., McPherson and Holcomb, 1999). In the latter study, pairs of semantically related objects were judged by subjects for relations' strength, and were accordingly classified to highly-related, moderately-related and unrelated pairs. Relations strength affected both subjects' behavior on judging if the pairs are related or not (being faster for highly related than for moderately related), and the evoked neural response (an N400 effect; see below).

Yet in the above study, relations – both strong and weak – were based on simple associations. That is, objects were considered to be related if they tended to co-appear (e.g., be associatively related, like hamburger and fries). Notably, such associative relations are different for objects than for words: when using verbal stimuli, associative relations rest on co-occurrence in language, so that more arbitrary associations can also be formed. For example, the words 'iceberg' and 'lettuce' are associatively, but not semantically, related (Thompson-Schill et al., 1998). For objects, on the other hand, associative relations rest on co-occurrences in the external world, within specific contexts or scenes (Bar, 2004; Gronau et al., 2008). Thus, the latter almost inevitably imply semantic relatedness, and are not arbitrary.

This allows us to suggest a different classification of relations within the semantic domain: relations that rest upon co-occurrences, like the ones studied above (e.g., pictures of a flower and a funnel), vs. more abstract, conceptual relations, in which a common concept ties between the objects, rather than their tendency to co-appear (e.g., pictures of a flower bud and a baby; flower buds do not necessarily appear next to babies in real life, but they are still semantically related to them, as both convey the concept of 'beginning'). While associative relations, which are based on co-occurrences, could be based on mechanisms of statistical learning or combinatorial semantics (e.g., Pulvermüller, 2013), more abstract relations might rely semantic knowledge, possibly involving also metaphorical processing (Holyoak and Stamenković, 2018). Alternatively, the two relations types might not involve different mechanisms, but rather differ only by strength; that is, one might claim that understanding the relations between a flower bud and a baby is simply a matter of greater semantic distance between the two, as compared to understanding the relations between a flower and a funnel.

This question has not yet been directly addressed, but findings from previous studies can be taken as evidence for each of these two alternatives. Abstract relations – defined here as relations between objects that do not tend to co-appear yet are still judged as related, or conveying a common concept – may indeed require more metaphorical reasoning, when deciphering the relations between the items. Such reasoning can be evoked by pictorial stimuli, as metaphors are not restricted to a specific modality but are fundamentally conceptual (Lakoff, 1993; Forceville, 2007). Thus far, however, metaphorical relations have been studied mostly using words (e.g., presenting pairs like 'lucid mind' and 'transparent intention', as opposed to literal pairs like 'burning fire' or 'problem resolution'; (Arzouan et al., 2007; very few studies, mostly focusing on advertisement and marketing, also probed visual metaphors: see Forceville, 2007; Indurkhya and Ojha, 2017; Ortiz et al., 2017; Ortiz, 2011)). In the above studies, metaphorical pairs evoked neural markers of enhanced processing, suggesting that they might either demand more processing resources (Arzouan et al., 2007; Schneider et al., 2014; De Grauwe, Swain, Holcomb, Ditman & Kuperberg, 2010; Coulson and Van Petten, 2002) or require additional, different mechanisms altogether (Arzouan et al., 2007; Mashal et al., 2007). In addition, some studies suggest differential hemisphere involvement in metaphor processing (Arzouan et al., 2007; Schmidt and Seger, 2009; Schmidt et al., 2010; Cardillo et al., 2012; Schneider et al., 2014; Stringaris et al., 2007; though see Rapp et al., 2012; Coulson and Van Petten, 2007, which found no such differences).

Outside the field of metaphor processing, abstract knowledge in general – either involving understanding abstract terms (Christoff et al., 2009), abstract rules (Badre & D'esposito, 2009) or more abstract relations (Krawczyk et al., 2010) – was suggested to involve unique neural substrates, being more anterior along a caudal-rostral axis (Badre & D'esposito, 2009; Christoff et al., 2009; Pulvermüller, 2013). Arguably, more anterior prefrontal areas combine different meanings of more abstract categories, so that the word 'seed', for example, gradually becomes connected to more complicated concepts, from 'a seed of an idea' to the concept of the 'lifecycle' (Speed, 2010). And so, specialized anterior areas are held to be needed for processing relations of greater complexity and wider semantic connections. Based on these findings, then, one might expect abstract relations to involve *qualitatively* different mechanisms than associative relations.

Alternatively, relations judgments – whether associative or abstract – might simply rely on finding a match between automatically activated verbal associations (Neely, 1977; Collins and Loftus, 1975; Tversky, 1977), evoked by each pictorial stimulus. That is, when the two pictures appear, each of them activates a series of related concepts (or nodes); once a match is made, so that the same node is activated by both pictures, they are judged to be related. Under this account, then, associative and abstract pairs will only *quantitatively* differ in ease of reaching a match, and not in the underlying processing mechanism.

Critically, these two alternatives imply different predictions about their electrophysiological correlates. If abstract relations only quantitatively differ from associative relations, one should expect the two types of relations to evoke the same component, possibly modulating its strength (i.e., its amplitude). Such effects are more likely to be found for three components. The first is the widely studied N400 (Kutas and Hillyard, 1980a, 1980b; see Kutas and Federmeier, 2011 for an exhaustive review). N400 was first described by Kutas and Hillyard (1980a; 1980b) as a more negative deflection occurring 300–500 ms post-stimulus for unexpected sentence endings compared to expected ones (Kutas and Hillyard, 1980a, 1980b). Interestingly, N400 amplitude is known to be modulated by relations' strength, with strongly-related pairs evoking the weakest amplitude, moderate relations yielding an intermediate amplitude, and unrelated pairs giving rise to the strongest, most negative amplitude. This was found both for object pairs (McPherson and Holcomb, 1999; see also Barrett and Rugg, 1990; Ganis et al., 1996 for use of objects, yet without manipulating relations strength) and for words (Frishkoff, 2007; Kutas and Hillyard, 1984). In the metaphors literature, a similar modulation of N400 amplitude was reported on the literality-metaphoricity or 'novelty' axis, such that literal pairs showed the weakest N400 amplitude, followed by conventional metaphors, which in turn elicited weaker waveforms than novel metaphors, and lastly unrelated pairs evoked the most negative, strongest N400 (Arzouan et al., 2007; De Grauwe, Swain, Holcomb, Ditman & Kuperberg, 2010; Coulson and Van Petten, 2002).

Several different interpretations of the N400 component have been offered. Some claim that it indexes semantic integration or combinatorial processes (Brown and Hagoort, 1993; Hagoort and Brown, 1994; Holcomb and Mcpherson, 1994; Friederici et al., 1999; McPherson and Holcomb, 1999; Kutas and Van Petten, 1994), where novel concepts are integrated or combined into the current representation (Baggio and Hagoort, 2011). Yet a more current and widely accepted view claims that integration only occurs later in the processing stages (see below), and suggest that the N400 actually reflects the violation of previously-laden expectations (Federmeier and Kutas, 1999, 2001; 2002; Federmeier, 2007), or retrieval from long term memory (Kutas and Federmeier, 2011; Lau et al., 2008; Arzouan et al., 2007; De Grauwe et al., 2010). Finally, recent opinions point to a more complex view, contending that both prediction processes influencing semantic retrieval and plausibility assessment processes affecting combinatorial or integration processes might be reflected in the N400 time-window (Nieuwland et al., 2019). Critically, under all interpretations, if indeed abstractly-related and associatively-related pairs (henceforth, 'abstract pairs' and 'associative pairs') lie on a continuum, a gradual modulation of N400 should be evoked. This is because abstract pairs should be harder to integrate, less expected and harder to retrieve than associative pairs (in which the items possibly also share greater semantic feature overlap; Neely, 1977), but easier to integrate, more expected and easier to retrieve than unrelated pairs. Such a result will be in line with previous findings where relations strength (McPherson and Holcomb, 1999; Barrett and Rugg, 1990) or metaphoricity (Arzouan et al., 2007; De Grauwe, Swain, Holcomb, Ditman & Kuperberg, 2010; Coulson and Van Petten, 2002) were manipulated.

The second component of interest is the Late Negativity, found mainly using words – either related/unrelated (Lau et al., 2013) or literal/metaphorical (Coulson and Van Petten, 2002; De Grauwe et al., 2010; Yang et al., 2013) – but also with pictorial stimuli (Cohn and Kutas, 2015). The Late Negativity immediately follows the N400, and is held to reflect reinterpretation processes, especially when integration is harder to achieve (e.g., when a novel meaning should be formed, or distant integration of meaning is required). Notably however, Late Negativity was also found in memory studies, where it was interpreted as a marker of working memory load (King and Kutas, 1995; Mecklinger and Pfeifer, 1996; Ruchkin et al., 1992; Steinhauer et al., 2010; Friederici et al., 1999).

Finally, the Late Positivity Component (LPC; sometimes referred to as P600; Rataj, Przekoracka-Krawczyk & van der Lubbe, 2018; DeLong et al., 2014; note though that others claim this component is actually the P3b component, indexing novelty/unexpected events; Bornkessel-Schlesewsky et al., 2011; Coulson et al., 1998) refers to a group of positive waves that sometimes also follow the N400. They are assumed to index integration and reanalysis in the face of anomalies or conflicting representations, for the purpose of arriving at a coherent and reasonable interpretation/representation of the stimuli (Brouwer et al., 2012; Kuperberg, 2007; Van de Meerendonk et al., 2009). A more nuanced distinction is made between a more left-frontal LPC related more to prediction mismatch and suppression of a predicted word to allow for integration of the actual input (Federmeier, 2007; Ness and Meltzer-Asscher, 2018) and a more parietal one related to plausibility violations (Nieuwland et al., 2019; Van Petten and Luka, 2012; DeLong et al., 2014). Notably, several studies yielded conflicting results regarding the LPC, where in some studies its amplitude was larger for novel, unexpected but plausible stimuli, compared with both expected and plausible stimuli and unexpected but implausible stimuli (Coulson and Van Petten, 2002; De Grauwe et al., 2010; Weiland et al., 2014) And in other studies, the opposite effect was found, with unexpected but plausible stimuli evoking a smaller LPC than expected and plausible stimuli (Arzouan et al., 2007; Rutter et al., 2012; Goldstein et al., 2012; Rataj, Przekoracka-Krawczyk & van der Lubbe, 2018). These conflicting results were suggested to reflect an interaction between the LPC and the Late Negativity, given their overlapping time window (Rataj et al., 2018). Because abstract pairs might require additional resources in later stages of reanalysis, they might evoke a larger LPC amplitude than associative or unrelated pairs, but may also show larger late negativity amplitude than associative pairs since only in the abstract condition a novel meaning should be processed.

Alternatively, if abstract pairs evoke some unique mechanism, a non-linear, non-gradient-like pattern should be found. This could either be manifested, for example, by laterality effects of relations' type (e.g., Arzouan et al., 2007; Schneider et al., 2014), or by some unique component which has yet to be found (as our experimental contrast has yet to be performed in previous studies), evoked only by abstract pairs and not by associative ones.

Accordingly, in two experiments we presented pairs of images that were either associatively related (i.e., tending to co-appear), abstractly related (i.e., semantically related though not tending to co-appear), or unrelated. In the first experiment, pairs were sequentially presented, while in the second they were simultaneously presented, to distill effects of expectations and online-relations processing. EEG was recorded while subjects explicitly judged if the pairs were related or not. We focused on the 300–500 ms and 500–700 ms time windows, in line with our components of interest, and hypothesized that a gradual modulation of amplitude in the expected order (unrelated-abstract-associative) should be found, given the above. We further reasoned that an additional, non-linear/gradual difference (e.g., in the lateralization of the effect), would imply also a qualitative mechanism for processing abstract relations.

2. Experiment 1

2.1. Introduction

Experiment 1 was aimed at examining the waveforms evoked by associative, abstract and unrelated pairs, presented sequentially. That is, first one image in the pair was presented, and then a second image followed. This follows previous studies, which typically used sequential presentation to probe relation processing (e.g., McPherson and Holcomb, 1999) and evoke priming from the first item to the second (Neely, 1977; Neely et al., 1989). We focused our search for a gradual/non-gradual effect on the time windows of the N400 (Kutas and Federmeier, 2011) component and that of the LPC (Rataj et al., 2018; DeLong et al., 2014) and Late Negativity (Coulson and Van Petten, 2002; De Grauwe et al., 2010; Lau et al., 2013; Yang et al., 2013).

2.2. Methods

2.2.1. Participants

Sixteen Tel Aviv University students participated in Experiment 1 (10 Females, 15 right handed, mean age = 24.50, SD = 1.80) for course credit or monetary compensation (~10$ per hour). All subjects reported normal or corrected-to-normal vision, no color blindness, no diagnosed psychiatric or neurological disorders, and no diagnosed hyperactivity or attention disorders. All subjects signed an informed consent to participate in the study, which was approved by the ethics committee of Tel Aviv University. Two additional subjects were excluded from the study due to high artifact rejection or lower consistency in the abstract condition resulting in less than 30 trials per condition. The study, including these exclusion criteria, was preregistered in the OSF website (https://osf.io/c56bu/?view_only=6c664c3514a34ce294c3deb1cc76753a), where all data and experimental codes are also available. Sample size was determined based on the work of McPherson and Holcomb (1999), which is most similar to our study. As their paper did not include the exact measures used to determine sample size (i.e., variance measures or effect sizes), we could not assess power and compute required sample size. Thus, we decided to use a sample size which is 1.5 times larger than theirs (N = 12). Note that the sample size in Experiment 2 was already based on the results of Experiment 1 (see below).

2.2.2. Stimuli

The stimuli consisted of pairs of images depicting common objects, persons or scenes, taken from Internet sources. The images were modified in Photoshop CS6: the critical stimuli were cut from their original background and inserted into a grey (RGB: 128, 128, 128) background, and the entire image was resized to 1200 × 850 pixels and 300 dpi. The

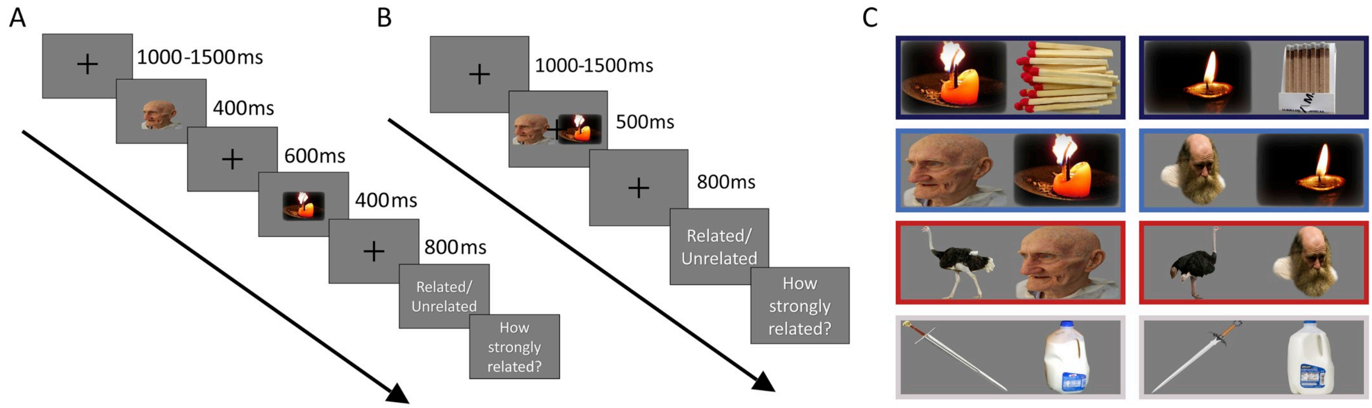

Fig. 1. Trial procedure in Experiment 1 (A) and 2 (B), as well as examples for stimuli pairs in the different conditions (C): two exemplars (left, right columns) of a pair used in the experiments: matches and a burning candle which tend to co-appear (Associative relation in dark blue), an old man and a dying out candle, conveying the concept of "End" while not tending to co-appear (Abstract relation in light blue), an old man and an ostrich (Unrelated in red) and a milk bottle and a sword – filler added to the experiment to equate the number of related and unrelated trials throughout the experiment (not analyzed; Novel Unrelated in light grey).

creation of the stimuli bank began with the abstract pairs and continued to the other pairs, in the following manner: originally, sixty-nine pairs were created so they would convey abstract relations (e.g., a dying out candle and an old man conveying the concept of End; see Fig. 1C). To each image in these pairs, an additional image of an object, a person or a scene, that tends to co-appear with that image was added, so to form two pairs that convey associative relations (e.g., matches for the candle, a walker for the old man; see Fig. 1C). Then, two other images – serving as associative counterparts for other abstract pairs - were used to create the unrelated pairs (e.g., candle and a lamb, old man and an ostrich; see Fig. 1C). Thus, the original stimuli bank contained 69 abstract, 138 associative and 138 unrelated pairs. For each pair, an additional version was prepared including different exemplars of the same objects, persons or scenes (e.g., different matches and a different candle; see Fig. 1C). This second set, consisting of the same pairs yet with different pictures or exemplars, was used to minimize the repetition between blocks (see below; critically, block assignment was randomly determined for each pair, so there were no systematic differences between blocks. That is, it was not the case that set 1 was used for block 1 and set 2 was used for block 2). Therefore, there were two sets, 345 pairs each, which were identical conceptually but not perceptually.

To validate the stimuli, a pilot experiment (N = 15, 9 Females, mean age = 24.5, SD = 2.72) was conducted in the lab, and a more in-depth on-line survey (N = 157, 82 Females, mean age = 29.5, SD = 4.53) was conducted on Qualtrics platform (the full results of both will be reported elsewhere). Here, we focus on three questions from the pilot and validation survey that were used in order to select stimuli for the current experiments: (a) are the pairs related or not; (b) what is their relation type, among three options: 'simple', 'abstract' and 'unrelated' (the word 'simple' was used since we did not think subjects would easily comprehend the meaning of associative relations); (c) if related, rate the strength of the relation on a 1 (very weak) to 5 (very strong) Likert scale. The 210 highest scoring pairs were chosen based on Question (a) - pairs that had the highest consistency with our predefined stimulus category of related or unrelated. So the final stimuli list for these studies includes two sets of 35 abstract related pairs, two sets of 35 associative related pairs and two sets of 35 unrelated pairs.

The relations of the chosen pairs were rated by most subjects in line with our predefined relations types (Qa), and relation strength was also consistent with our definitions (Qc). Relation type, measured in the online survey, further matched our classifications (Qb). Table 1 summarizes all results, collapsed across both sets, as well as separately. Importantly, the two sets were well correlated with one another, both with respect to relations judgements and even more so, to relations' strength.

In addition to the above stimuli, two sets of "novel unrelated" pairs were created, which – unlike the previous classes of pairs – included objects, persons or scenes that did not appear in any of the other conditions (see again Fig. 1C). This condition was created as a filler, in order to equate the number of "related" vs. "unrelated" trials in the experiment, hereby avoiding any response biases.

2.2.3. *Apparatus*

Stimuli were presented on a 24″Asus LCD HDMI monitor (VG248QE) with 1920*1080 pixels and 144-Hz refresh rate, using Matlab and Psychtoolbox 3 (Brainard and Vision, 1997; Pelli, 1997). They appeared on a grey background (RGB: 128, 128, 128) at the center of the screen (9.5° × 6.4° visual angle). Subjects were sited in a dimly lit room 60 cm away from the screen.

2.2.4. *Procedure*

The experiment included 280 self-paced trials, divided into two blocks with three breaks, one in the middle of each block and another between blocks. In each block, half the trials included an unrelated pair (unrelated/novel unrelated), and the other half – a related pair (associative/abstract). All 140 pairs (70 related: 35 Abstract, 35 Associative, 70 Unrelated: 35 Unrelated, 35 Novel unrelated), were presented in each block, and were accordingly repeated in the second block, yet at a different presentation order and using different exemplars (Fig. 1C; e.g. left pairs were presented in block 1 and right pairs – in block 2 but in a different order). Thus, each participant saw 70 pairs in each condition across the two blocks. Accordingly, subjects were conceptually exposed to each pair twice, but perceptually – only once, given that different exemplars were used. Importantly, the assignment of exemplars to the different blocks was randomly determined for each subject, so to avoid any systematic differences between blocks (i.e., in each block subjects saw a mixture of stimuli from set 1 and 2). Any concern for systematic-low level differences between the conditions was further minimized thanks to the fact that each picture in the abstract condition appeared also in the two other conditions, and the appearance in each condition was randomized between subjects.

Trials were pseudo-randomly intermixed with the constraint that no condition repeats in more than three consecutive trials and no object, person or scene appears more than once within five consecutive trials. The order of the stimuli's first and second appearance within block, and between blocks, was random and unique for each subject.

At the beginning of the experiment, subjects were explained that their task is to determine if the pairs are related or not. They were advised to use two guiding questions: first, whether most people would agree that the pair is related, and second, whether they can think of a word that conveys the relation between the two. Then, the experiment began with eleven practice trials, in which feedback from the

Table 1

Validation results for the stimuli, with respect to: (1) Relations judgement: means refer to percentage of participants who classified the pair as related. This measure further indicates how many participants misclassified the associative and abstract pairs as unrelated (1.18% and 13.42%, respectively), and how many misclassified the unrelated pairs as related (5.16%); (2) Relation type: means refer to percentage of participants whose classifications were consistent with our pre-defined stimulus type. (3) Relations strength: means refer to averaged strength score across participants. The outmost right column provides the correlations between the two sets, either across all relation types (upper rows), or within each type (in the corresponding row).

	Combined	Set 1	Set 2	Correlation
Relations judgment (Qa)				R = 0.65, F(1,103) = 75.62, p < 0.00001
Associative	M = 98.21, SD = 3.01	M = 97.86, SD = 3.32	M = 98.57, SD = 2.62	R = 0.42, F(1,33) = 6.95, p = 0.013
Abstract	M = 86.43, SD = 10.40	M = 86.96, SD = 8.50	M = 85.89, SD = 11.98	R = 0.42, F(1,33) = 7.02, p = 0.012
Unrelated	M = 94.38, SD = 8.06	M = 94.64, SD = 7.19	M = 94.11, SD = 8.83	R = 0.68, F(1,33) = 28.50, p < 0.00001
Relations type (Qb)				R = 0.77, F(1,103) = 149.06, p < 0.00001
Associative	M = 90.07, SD = 9.27	M = 88.74,SD = 9.95	M = 91.40, SD = 8.33	R = 0.71, F(1,33) = 33.04, p < 0.00001
Abstract	M = 63.30, SD = 16.35	M = 62.85, SD = 17.41	M = 63.75,SD = 15.20	R = 0.41, F(1,33) = 6.75, p = 0.014
Unrelated	M = 92.58, SD = 6.26	M = 92.76, SD = 5.01	M = 92.40, SD = 7.29	R = 0.34, F(1,33) = 4.28, p = 0.047
Relations strength (Qc)				R = 0.99, F(1,103) = 5118.48, p < 0.00001
Associative	M = 4.75, SD = 0.25	M = 4.72, SD = 0.24	M = 4.77, SD = 0.25	R = 0.82, F(1,33) = 69.35, p < 0.00001
Abstract	M = 3.76, SD = 0.47	M = 3.78, SD = 0.44	M = 3.73, SD = 0.50	R = 0.81, F(1,33) = 63.21, p < 0.00001
Unrelated	M = 1.23, SD = 0.25	M = 1.23, SD = 0.22	M = 1.22, SD = 0.28	R = 0.82, F(1,33) = 67.96, p < 0.00001

experimenter regarding the use of the two questions was given. During every break, subjects were reminded of these instructions and the use of the questions to make sure they stay focused and motivated. No feedback on their performance was given.

Each trial began with a fixation jitter of 1000–1500 ms, followed by a 400 ms presentation of the first image of the pair. Then, a blank screen with a fixation cross appeared for 600 ms, followed by the presentation of the second image of the pair, again for 400 ms. Finally, another blank appeared for 800 ms, followed by a question ("related/unrelated?") to which the subject responded by pressing with the right hand the right/left arrow keys (key assignment counterbalanced between subjects). This was followed by a second question ("How strongly related?"), prompting subject to rate the strength of the relation on a Likert scale of 1 = not related at all, to 5 = strongly related, with the left hand (Fig. 1A).

2.2.5. ERP recording

EEG was recorded from 64 electrodes (BioSemi Active Two system, the Netherlands) mounted on a cap following the extended international 10/20 system. Seven additional electrodes were used: two located on the mastoid bones, one located on the tip of the nose and four EOG channels: two placed at the outer canthus of each eye for horizontal eye movement monitoring, and two under and above the right eye for vertical eye movement monitoring. EEG was digitized at a sampling rate of 512 Hz, using a High pass filter of 0.05 Hz and no low-pass filter. Electrode impedances kept below 20 Kv.

2.2.6. ERP analysis

Preprocessing was conducted using the "Brain Vision Analyzer" software (Brain Products, Germany)For consistency with previous N400 studies (Kutas and Federmeier, 2011), data from all channels was referenced offline to the average of the mastoid channels. The data was digitally high-pass filtered at 0.1 Hz (24dB/octave) to remove slow drifts, using a Butterworth zero-shift filter, and then digitally notch-filtered at 50 Hz to remove electrical noise. Bipolar EOG channels were calculated by subtracting the left from the right horizontal EOG channel, and the inferior from the superior vertical EOG channels, to emphasize horizontal and vertical eye movement artifacts. The signal was cleaned of blink and saccade artifacts using Independent Component Analysis (ICA) (Jung et al., 2000). A semi-automatic artifact removal procedure was used to detect and remove segments with artifacts (amplitudes exceeding 100 mV, differences beyond 100 mV within a 200 ms interval, or activity below 0.5 mV for over 100 ms). Specific channels exceeding 20% rejection rate on valid trails were interpolated (spline, Order: 4, Degree: 10, Lambda: 1E-05) resulting in one subject having three electrodes interpolated in Experiment 1, and one subject having one electrode interpolated in Experiment 2.

EEG data was segmented into 1000-ms long epochs starting 100 ms prior to the second image onset. Trials in which subjects gave the wrong answer, took longer than 5s to respond or had reaction times (RTs) longer than three standard deviations from their average in each condition were excluded. Segments were then averaged separately for each condition (means and SD of the average number of trials for each condition that were included in the analysis: novel unrelated [Experiment 1: M = 62, SD = 4; Experiment 2: M = 58, SD = 6], unrelated [Experiment 1: M = 60, SD = 6; Experiment 2: M = 58, SD = 7], abstract [Experiment 1: M = 55, SD = 8; Experiment 2: M = 52, SD = 6], associative [Experiment 1: M = 62, SD = 4; Experiment 2: M = 62, SD = 3]). Average waveforms were low-pass filtered using a Butterworth zero-shift filter with a cutoff of 30 Hz, and the baseline was adjusted by subtracting the mean amplitude of the prestimulus period of each ERP from all the data points in the segment. For visual purposes alone the waveforms for the graphs were low-pass filtered using a Butterworth zero-shift filter with a cutoff of 12 Hz.

To reduce the number of comparisons, electrode data was pooled to nine areas (Left, Middle, Right X Frontal, Central, Parieto-Occipital; Mudrik, Lamy & Deouell, 2010; Mudrik et al., 2014: Left Frontal [Fp1, AF3, AF7, F3, F5, F7]; Middle Frontal [Fpz, AFz, Fz, F1, F2]; Right Frontal [Fp2, AF4, AF8, F4, F6, F8]; Left Central [FC3, FC5, FT7, C3, C5, T7, CP3, CP5, TP7]; Middle Central [FCz, FC1, FC2, Cz, C1, C2, CPz, CP1, CP2]; Right Central [FC4, FC6, FT8, C4, C6, T8, CP4, CP6, TP8]; Left Parieto-Occipital [P3, P5, P7, P9, PO3, PO7, O1]; Middle Parieto-Occipital [Pz, P1, P2, POz, Oz, Iz]; Right Parieto-Occipital [P4, P6, P8, P10, PO4, PO8, O2]).

Two types of analyses were conducted (both preregistered). First, in a 'Time of interest' analysis, we compared the average amplitude within pre-defined windows of 300–500 ms and 500–700 ms, using a three-way ANOVA with Region (Frontal, Central, Parieto-occipital), Laterality (Left, Midline, Right) and Relation type (Unrelated, Associative and Abstract) as factors (the novel unrelated condition was not analyzed, as it was merely a filler condition). In all ANOVA analyses, Greenhouse and Geisser (1959) correction was used where needed (epsilon and uncorrected degrees of freedom are reported; Picton et al., 2000). The Benjamini–Hochberg procedure (Benjamini and Hochberg, 2000) was used to correct for multiple comparisons across the entire manuscript (i.e., multiple ANOVAs; note that we only report and correct for effects of interest - that is, effects involving Relation Types. We also correct separately for EEG and behavioral findings, yet we perform the correction across both experiments, so to correct for all the potentially-reportable effects across the manuscript; Benjamini et al., 2001).

Second, to search for unique differences induced by the abstract related pairs, a cluster-based non-parametric permutation statistical analysis (Maris and Oostenveld, 2007) was ran for each of the main contrasts (Unrelated - Associative, Unrelated - Abstract, and Associative - Abstract) within a 200–900 ms time window. This time window was chosen to allow for a more exploratory analysis over the entire time window, but assuming that no differences should be found within the first 200 ms, given the relatively high-level nature of the processes at hand. To correct for multiple comparisons, alpha threshold was divided by the number of comparisons ($\alpha = 0.05/9 = 0.0056$). Besides these confirmatory analyses, we ran an additional post-hoc exploratory analysis, in which the data was separated into blocks in order to track repetition effects between the blocks (e.g., Bentin and McCarthy, 1994; Besson et al., 1992; Van Petten and Senkfor, 1996). Standard Errors in all graphs were adjusted for repeated measures (Cousineau, 2005; Morey, 2008). Effect size measures (partial eta squared and Cohen's d) are reported alongside Null Hypothesis Significance Testing.

2.3. Results

2.3.1. Behavioral results

As expected, both subjects' consistency with our predefined stimuli type (i.e., the percentage of participants who classified the pair in consistency with our pre-defined stimulus type) ($F(3, 45) = 16.98$, $p = 0.0006$, $\varepsilon = 0.41$, $\eta_p^2 = 0.53$) and their reaction times ($F(3, 45) = 13.15$, $p = 0.0002$, $\varepsilon = 0.68$, $\eta_p^2 = 0.47$) were strongly modulated by Relation type (Fig. 2A). Post-hoc Tukey tests revealed that subjects were consistent with our predefined stimulus category for abstract pairs, yet to a lesser degree ($M = 85.29$, $SD = 10.12$) compared with both associative pairs ($M = 98.55$, $SD = 1.82$; $p < 0.0001$, $d = 1.82$) and unrelated ones ($M = 96.99$, $SD = 2.47$; $p < 0.0001$, $d = 1.59$). Associative pairs did not differ in consistency from unrelated pairs ($p = 0.905$, $d = 0.72$). Similarly, there was no difference between the unrelated and novel unrelated conditions ($M = 96.51$, $SD = 3.83$; $p = 0.997$, $d = 0.15$).

Reaction times revealed somewhat different patterns (Fig. 2B): associative pairs ($M = 0.54$, $SD = 0.16$) evoked faster responses not only compared to abstract pairs ($M = 0.69$, $SD = 0.20$; $p < 0.0001$, $d = 0.83$), but also to unrelated ones ($M = 0.64$, $SD = 0.17$; $p = 0.006$, $d = 0.62$). Here, abstract pairs did not differ from unrelated pairs ($p = 0.35$, $d = 0.27$), and again there was no difference between the unrelated and novel unrelated conditions ($M = 0.68$, $SD = 0.21$; $p = 0.52$, $d = 0.22$).

Subjects' ratings of relation strength further validated our manipulation ($F(3, 45) = 453.19$, $p < 0.0001$, $\varepsilon = 0.43$, $\eta_p^2 = 0.97$; Fig. 2C). Associative pairs were rated as most strongly related ($M = 4.61$, $SD = 0.31$), followed by abstract pairs ($M = 3.72$, $SD = 0.61$; $p < 0.0001$, $d = 1.84$, for the difference between associative and abstract) and finally unrelated pairs ($M = 1.12$, $SD = 0.18$; $p < 0.0001$, $d = 13.78$, for the comparison with associative pairs; $p < 0.0001$, $d = 5.81$, for the comparison with abstract ones). No difference in ratings was found between the unrelated and the novel unrelated conditions ($M = 1.12$, $SD = 0.21$; $p = 1$, $d = 0.01$ See Figs. 2-1). Note that these ratings are based on correctly classified pairs only.

2.3.2. EEG results

Overall, a graded pattern was found in some sites, supporting a quantitative difference between associative and abstract pairs (Fig. 3). The effect was spread across the scalp. The cluster-based permutation analysis revealed that the differences between unrelated pairs and both associative and abstract ones began as early as ~300 ms post-stimulus onset (296 ms and 302 ms, respectively; note that this should not be mistaken as the latency or onset of the effects, which might start later on in time; Sassenhagen and Draschkow, 2019). However, the difference between associative and abstract pairs was less prominent (detected only when not correcting for multiple comparisons, with $\alpha = 0.05$), and started only at 370 ms.

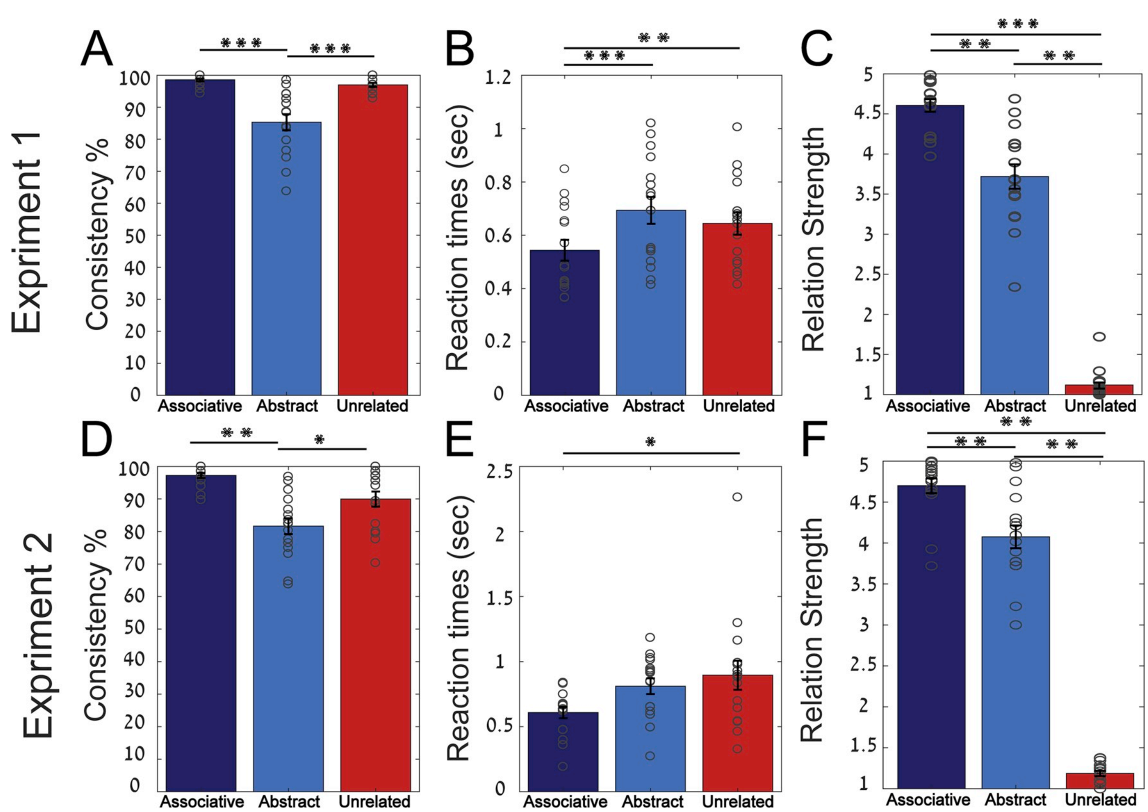

Fig. 2. Mean proportion of relatedness judgments that were consistent with the predefined stimulus category (Exp.1: A, Exp. 2: D), reaction times (Exp.1: B, Exp. 2: E) and relations strength scores (Exp.1: C, Exp. 2: F) for the three conditions. Individual subjects represented with circles. Significant differences are marked with three stars ($p < 0.0001$), two stars ($p < 0.001$) or one star ($p < 0.05$). (See Supp-Figs. 2-1 for the filler condition).

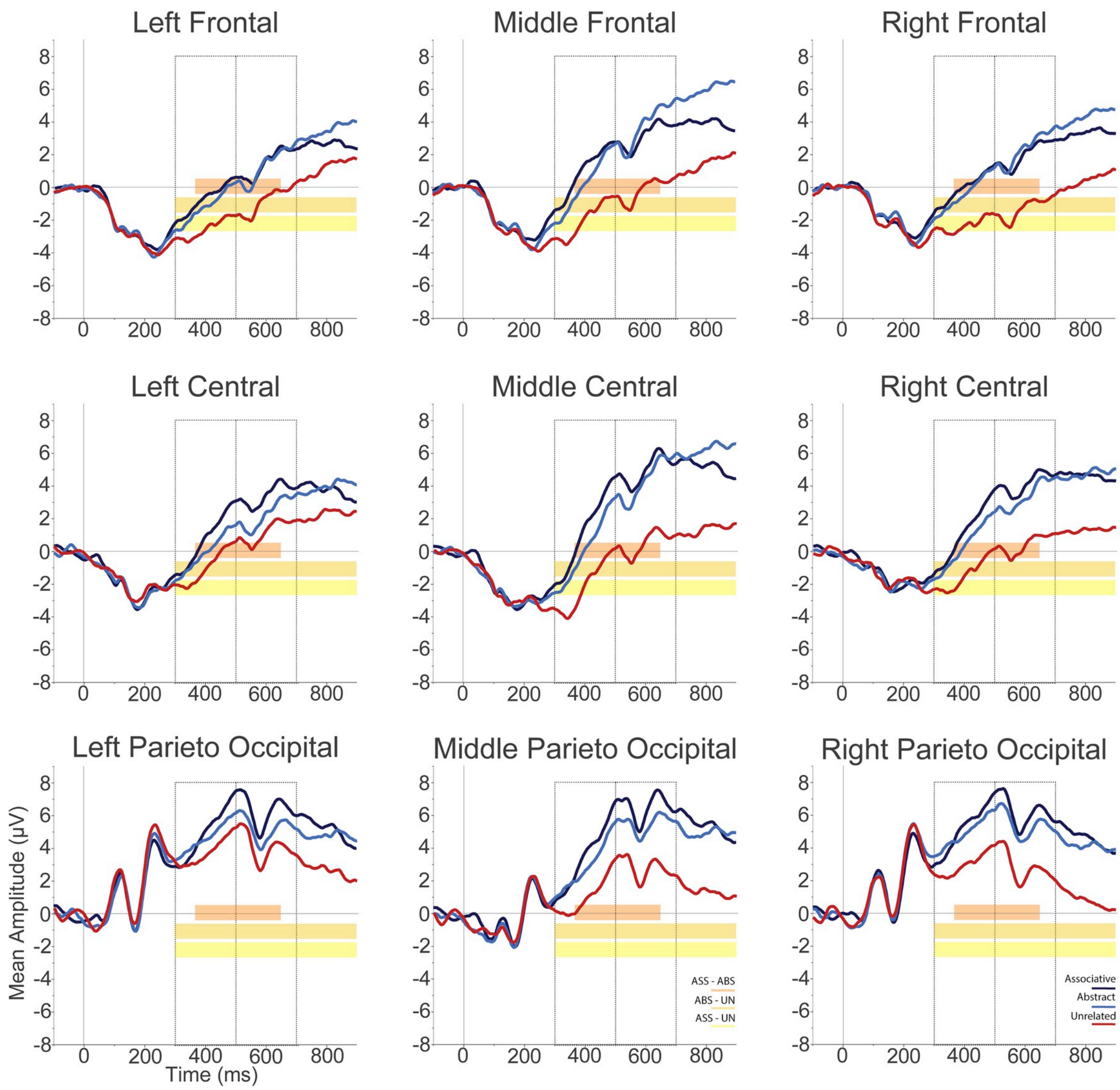

Fig. 3. Mean waveforms from Experiment 1 elicited by associative pairs (dark blue), abstract pairs (light blue), and unrelated pairs (red), for all regions. Light yellow patches indicate significant clusters for the difference between associative and unrelated pairs (as revealed by a cluster-based permutation analysis), light orange patches mark periods of significant difference between abstract and unrelated pairs, and darker orange patches indicate differences between associative and abstract pairs. The 300–500 ms and 500–700 ms time windows are framed with dotted lines. (See Supp-Figs. 3-1 for the filler condition). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.3.2.1. 300–500 time window. ANOVA with Region, Laterality and Relation type revealed a main effect for Relation type ($F(2, 30) = 16.46$, $p < 0.0001$, $\eta_p^2 = 0.52$), a two-way interaction of Relation type and Laterality ($F(4, 60) = 9.79$, $p < 0.0001$, $\eta_p^2 = 0.39$) and a three-way interaction between all factors ($F(8, 120) = 2.25$, $p = 0.043$ (note again that all p-values are FDR-corrected), $\eta_p^2 = 0.13$). To explore the source of the interaction, a post-hoc Tukey test was conducted (see results in Table 2), showing that while associative and unrelated pairs – as well as abstract and unrelated pairs – differed in all nine areas, associative and abstract pairs differed mostly at left and middle areas. Thus, it seems that while in most right electrodes associative and abstract pairs tended to elicit a similar response (which was different from that evoked by unrelated pairs), at middle and left sites there was a gradual modulation of the amplitude by condition: associative pairs elicited the least negativity, unrelated pairs the greatest negativity, and abstract pairs were in between these two waveforms.

2.3.2.2. 500–700 time window. A similar, yet more pronounced, pattern was found in the late window; a main effect for Relation type was found ($F(2, 30) = 28.54$, $p < 0.0001$, $\eta_p^2 = 0.66$), as well as two-way interactions of Relation type and Laterality ($F(4, 60) = 18.93$, $p < 0.0001$, $\eta_p^2 = 0.56$) and of Relation type and Area ($F(4, 60) = 8.47$, $p = 0.003$, $\varepsilon = 0.52$, $\eta_p^2 = 0.36$). Finally, a three-way interaction between all factors was also found ($F(8, 120) = 4.44$, $p = 0.008$, $\varepsilon = 0.50$, $\eta_p^2 = 0.23$). Again, post-hoc Tukey test (see Table 3) revealed that associative and unrelated pairs, as well as abstract and unrelated pairs, differed in all nine areas. Different from the N400 time window, here associative and abstract pairs differed in all but Left Frontal and Right Frontal areas. Thus, in the late time window, the gradual pattern of unrelated pairs being the most negative followed by abstract pairs, which in turn are more negative than associative pairs, was not lateralized as in the earlier time window. Note that in this time window, in frontal areas abstract pairs were actually more positive than associative pairs (MF: $p = 0.0285$; $d = -0.14$; abstract mean amplitude = 3.74, SD = 3.63; associative mean amplitude = 3.22, SD = 4.06), as opposed to central and parieto-occipital areas where they were more negative.

2.3.2.3. Blocks analysis. Aside from the above confirmatory analysis,

Table 2
p values (top rows in each cell) and Cohen's d (bottom rows) for the post-hoc Tukey test conducted following the ANOVA on the 300–500 ms, for the three main contrasts, within each region.

	Frontal sites			Central sites			Parieto-occipital sites		
	Left	Middle	Right	Left	Middle	Right	Left	Middle	Right
Associative vs. Unrelated	$p < 0.0002$ $d = 0.44$	< 0.0002 0.62	< 0.0002 0.51	< 0.0002 0.63	< 0.0002 1.03	< 0.0002 1.04	< 0.0002 0.42	< 0.0002 0.92	< 0.0002 0.61
Abstract vs. Unrelated	$p < 0.0002$ $d = 0.33$	< 0.0002 0.46	< 0.0002 0.43	< 0.0002 0.35	< 0.0002 0.68	< 0.0002 0.74	< 0.0002 0.31	< 0.0002 0.68	< 0.0002 0.54
Associative vs. Abstract	$p < 0.005$ $d = 0.12$	< 0.0002 0.18	n.s.	< 0.0002 0.31	< 0.0002 0.33	< 0.0002 0.30	n.s.	< 0.005 0.19	n.s.

we performed a post-hoc exploratory inspection of the data when divided to the two experimental blocks. Notably, in the second block subjects were already familiar with the pairs (though with different exemplars; the pairs were conceptually but not perceptually identical). Previous studies showed that repetition affects N400 and the late components and diminishes their amplitude (N400: Bentin and McCarthy, 1994; Besson et al., 1992; the Late negativity was not directly tested with respect to repetition, but hints for such an effect can be found in Van Petten and Senkfor, 1996), so we wanted to re-examine our findings while focusing on first vs. repeated exposure to the pair. We thus repeated the above ANOVA analysis, yet adding block as another independent variable. For simplicity (as well as to minimize multiple comparisons), we unified the two time-windows of interest, which showed similar patterns in the above analysis, thus examining averaged amplitudes in the different conditions between 300 ms and 700 ms.

The four-way ANOVA analysis with Block, Region, Laterality and Relation type confirmed this interpretation, revealing an interaction of condition and block ($F(4, 60) = 3.82$, $p = 0.047$, $\eta_p^2 = 0.20$). A trend for a four-way interaction was also found ($F(8, 120) = 2.22$, $p = 0.0793$ corrected for sphericity violation only, $p = 0.10$ corrected also for multiple comparisons, $\varepsilon = 0.49$, $\eta_p^2 = 0.13$). Interestingly, this marginal interaction seems to be driven by a differential response to the abstract pairs in the first and second blocks: in block 1, associative pairs differed in all nine areas from unrelated pairs, as well as from abstract pairs (see Table 4), while abstract and unrelated pairs differed in all areas but the LC and LPO. Strikingly, in block 2 the pattern was almost reversed: here abstract pairs differed from unrelated pairs in all nine areas *but not from* associative *pairs* in any of the areas but RF. This was further confirmed by the cluster-based permutation analysis in which abstract and associative pairs differed only in block 1 (see Fig. 4).

To further examine this shift and specifically to pinpoint the effect of block, we subtracted the waveforms of associative and abstract condition from the one evoked by the unrelated condition (in a way, this represents the divergence of each of those conditions from being tagged as 'unrelated' by relations-processing mechanisms). We conducted the same four-way ANOVA with Relation type (associative-unrelated, abstract-unrelated), Block, Laterality and Area. The only effect involving block and relation type was a four-way interaction ($F(4, 60) = 3.52$, $p = 0.0408$, $\varepsilon = 0.53$, $\eta_p^2 = 0.19$). Tukey post tests showed that the difference waves elicited by associative and abstract pairs (vs. the unrelated condition) differed in block 1 in all areas (LF: $p = 0.0009$; $d = -0.29$; MF: $p = 0.0011$; $d = -0.30$; RF: $p = 0.0005$; $d = -0.29$; LC: $p = 0.0002$; $d = -0.62$; MC: $p = 0.0002$; $d = -0.74$; RC: $p = 0.0002$; $d = -0.64$; LPO: $p = 0.0002$; $d = -0.61$; MPO: $p = 0.0002$; $d = -0.56$; RPO: $p = 0.0002$; $d = -0.35$) but almost did not differ in block 2 but in two areas (RF: $p = 0.0055$; $d = 0.25$; LC: $p = 0.0479$; $d = -0.27$).

Thus, the results above indeed imply that there might be a unique mechanism which is more sensitive to abstract relations, while another mechanism – tuned to associative relations –is unable, at first exposure, to even detect the abstract ones (ERPs recorded over left central and parieto-occipital cites did not differentiate between abstract and unrelated pairs during the first block, while right cites did).

2.4. Discussion

The results of Experiment 1 lend support for both a quantitative and a qualitative account of relations processing. The former is manifested mainly in the graded patterns observed both in the N400 and the late negativity components, as expected. This accords with previous studies, which found a similar modulation of N400 amplitude as a function of relations strength, both for object pairs (McPherson and Holcomb, 1999) and for words (Frishkoff, 2007; Kutas and Hillyard, 1984). The negativity we observed in both time-windows might also be interpreted as two components, or as some sort of a sustained N400 effect (which was previously found for object-scene relations, for example; Mudrik et al., 2010; Mudrik et al., 2014; and also in aphasia patients; Wilson et al., 2012).

Notably, in the 500–700 ms time window, we did not observe an LPC, though a positive effect for abstract pairs was found in right frontal sites. This positivity could also be interpreted as a P3b effect, which has been studied also in the context of semantic relations processing and metaphorical processing (Sassenhagen et al., 2014; Van Petten and Luka, 2012). This interpretation seems fitting given the task (explicit judgement relations), and given that P3 in general is commonly found also for surprising/unexpected stimuli (Donchin, 1981; Sutton et al., 1965). But this seems less likely in our case; first, because

Table 3
p values (top rows in each cell) and Cohen's d (bottom rows) for the post-hoc Tukey test conducted following the ANOVA on the 500–700 ms, for the three main contrasts, within each region.

	Frontal sites			Central sites			Parieto-occipital sites		
	Left	Middle	Right	Left	Middle	Right	Left	Middle	Right
Associative vs. Unrelated	$p < 0.0002$ $d = 0.60$	< 0.0002 0.81	< 0.0002 0.87	< 0.0002 0.72	< 0.0002 1.15	< 0.0002 1.41	< 0.0002 0.71	< 0.0002 1.06	< 0.0002 0.96
Abstract vs. Unrelated	$p < 0.0002$ $d = 0.60$	< 0.0002 0.99	< 0.0002 0.95	< 0.0002 0.37	< 0.0002 1.04	< 0.0002 1.16	< 0.0002 0.35	< 0.0002 0.80	< 0.0002 0.76
Associative vs. Abstract	n.s	< 0.03 0.14	n.s.	< 0.0003 0.42	< 0.001 0.17	< 0.0003 0.32	< 0.0003 0.36	< 0.0003 0.30	< 0.0003 0. 23

Table 4
p values (top rows in each cell) and Cohen's d (bottom rows) for the post-hoc Tukey test conducted following the ANOVA on the 300–700 ms, for the three main contrasts, within each region, and each block.

	Frontal cites			Central cites			Parieto-occipital cites		
	Left	Middle	Right	Left	Middle	Right	Left	Middle	Right
BLOCK 1									
Associative vs. Unrelated	p = 0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
	d = 0.48	0.73	0.71	0.57	1.17	1.19	0.40	0.82	0.65
Abstract vs. Unrelated	p = 0.0002	0.0002	0.0002	n.s.	0.0002	0.0002	n.s.	0.0002	0.0002
	d = 0.28	0.58	0.53		0.67	0.65		0.36	0.40
Associative vs. Abstract	p = 0.0006	0.0008	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
	d = 0.22	0.20	0.22	0.64	0.67	0.77	0.41	0.45	0.22
BLOCK 2									
Associative vs. Unrelated	p = 0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
	d = 0.52	0.67	0.59	0.69	0.98	1.06	0.70	1.05	0.86
Abstract vs. Unrelated	p = 0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
	d = 0.58	0.74	0.73	0.49	0.89	0.96	0.53	0.82	0.72
Associative vs. Abstract	n.s.	n.s.	0.0049	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
			0.15						

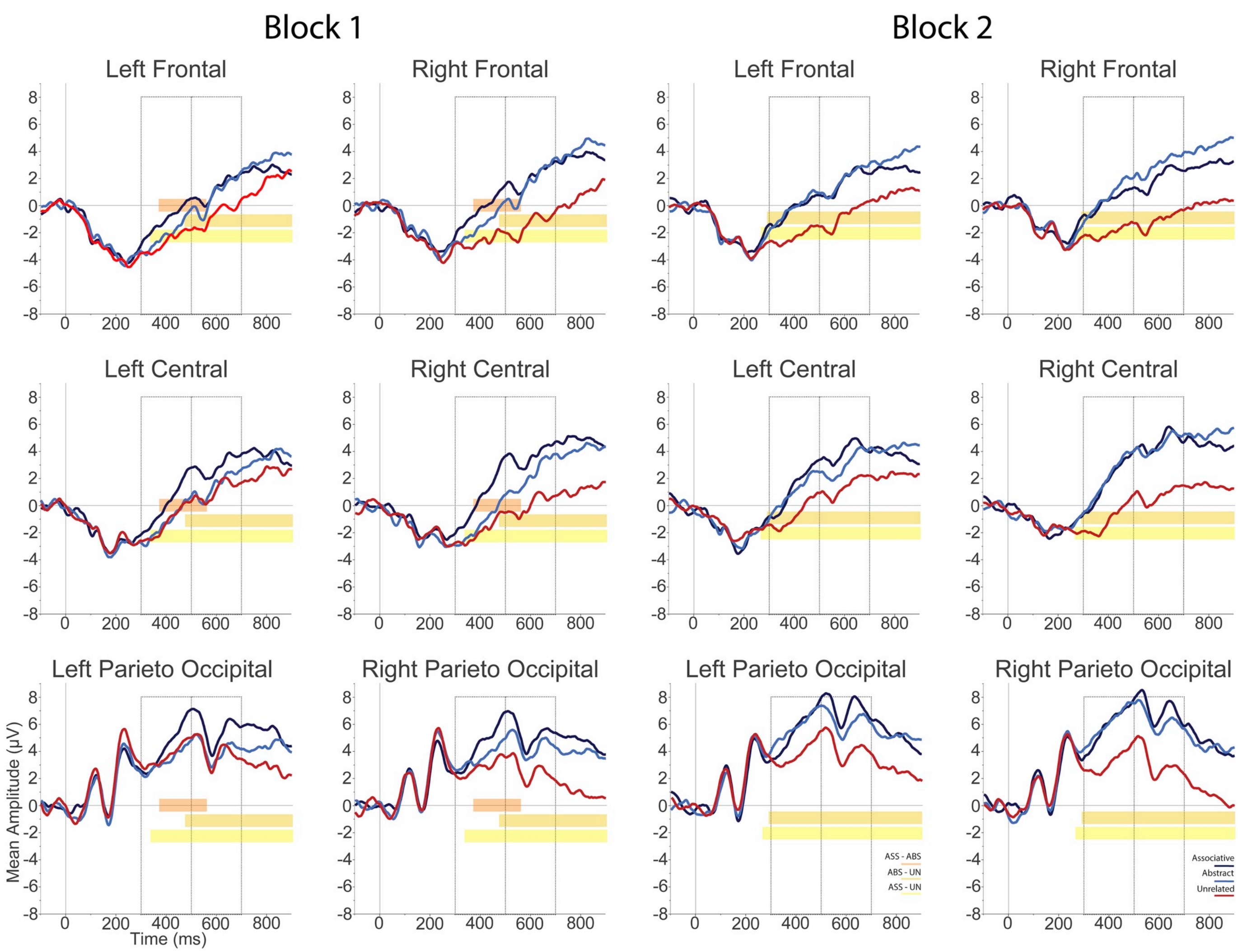

Fig. 4. Mean waveforms from Experiment 1 elicited by associative pairs (dark blue), abstract pairs (light blue), unrelated pairs (red), for left and right electrodes in block 1 and 2. Light yellow patches indicate periods in which associative and unrelated pairs differed (as revealed by a cluster-based permutation analysis), light orange patches mark periods of significant difference between abstract and unrelated pairs, and darker orange patches indicate differences between associative and abstract pairs. The 300–500 ms and 500–700 ms time windows are framed with dotted lines. (See Supp-Figs. 4-1 for the filler condition). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the distribution of the effect is very different than the P3 component. Second, because unrelated pairs are even more surprising than the abstract ones, yet no such positivity has been observed for them. Third, because abstract pairs and associative pairs evoke the same response, with respect to the task, yet again the effect was found only for abstract pairs. Future research is thus needed to better clarify this point.

As opposed to previous studies, here our relation classification did not rest only on strength, but also on relation type (associative vs. abstract). Thus, the graded pattern we found might also index some metaphorical processing that might be required to decipher abstract relations, as such processing was found to evoke a stronger N400 effect (Arzouan et al., 2007; De Grauwe, Swain, Holcomb, Ditman & Kuperberg, 2010; Coulson and Van Petten, 2002).

Interestingly, the findings also implied a qualitative difference between processing of the two relation types. This difference was reflected by the lateralized distribution of the effect, as revealed by the exploratory, post-hoc block analysis we conducted. Namely, in the first block, most left sites did not differentiate between abstract and unrelated pairs, while right sites did. At first sight, this seems to echo pervious hemispheric differences reported in the literature (e.g., Arzouan et al., 2007; Schneider et al., 2014). Yet, as we explain in the general discussion below, our findings cannot attest to such differences, as we did not manipulate laterality (e.g., by presenting the stimuli in different visual fields; Bourne, 2006). In addition, they rest on a marginally significant trend (yet strong effects in the follow-up analyses). Accordingly, they can only hint to a possible qualitative difference, and stress the need for further research which could directly examine this point.

A potential limitation of the current study is that we did not control for low-level visual features of the stimuli (e.g. familiarity, visual similarity and complexity). We did not expect any systematic differences in these features across conditions, since the same objects appear in all conditions. Yet such differences can of course occur; to estimate if this could have affected processing in any way, we looked for differences in the N1/P1 time window (120–200 ms), held to index sensory processing that is sensitive to the physical properties of the stimuli (Luck, 2014) and to attention allocation (for review, see Luck and Girelli, 1998). No differences were found between the conditions, mitigating this concern.

3. Experiment 2

3.1. Introduction

The findings of Experiment 1 might not necessarily reflect differences in online processing of these pairs, but rather differences in prediction, as the pairs were sequentially presented (note that the N400 was explicitly claimed to reflect the violation of previously-laden expectations; Metusalem et al., 2016; Federmeier, 2007). Thus, in Experiment 2 we presented the two images in each pair simultaneously rather than sequentially, so that participants will not form an expectation about the second stimulus in the pair prior to its presentation, based on the first one. If the results of Experiment 1 are indeed driven solely by prediction, they should not be replicated here. Alternatively, if they represent genuine semantic integration, they should also be found during simultaneous presentation.

3.2. Methods

3.2.1. Participants

Sixteen Tel Aviv University students participated in Experiment 2 (10 Females, 13 right handed, mean age = 24.5, SD = 2.4) for course credit or monetary compensation (~10$ per hour). Two additional subjects were excluded from the study due to high artifact rejection or low consistency resulting in less than 30 trials per condition (as only correctly classified trials were included in the analysis). Sample size was assessed based on the effects found in Experiment 1 using the G*Power software (Faul et al., 2007). We focused on the N400 main effect for relation types, as it was the main finding of Experiment 1 and accordingly the primary target of the replication attempt in Experiment 2. We found that keeping the same sample size (N = 16), with the observed effect, would give us power of > 99% (with $\alpha = 0.05$).

3.2.2. Stimuli, apparatus, procedure, recording and analysis

All parameters were identical to those used in Experiment 1, besides the following differences: first, the visual angle in which the images were presented was $9.5^\circ \times 3.2^\circ$; the images were combined to one and its size was reduced by half (compared to Experiment 1) so that the overall width of the pair – now presented simultaneously - would remain the same as it was in Experiment 1, to minimize eye movements between the images. Second, the images were simultaneously and not sequentially presented, and for 500 ms only (see again Fig. 1B). Finally, epochs were segmented to the pair onset.

3.3. Results

3.3.1. Behavioral results

Replicating the behavioral findings from Experiment 1, subjects' consistency was affected by Relation type ($F(3, 45) = 9.45$, $p = 0.0049$, $\varepsilon = 0.45$, $\eta_p^2 = 0.39$; Fig. 2D). Subjects were less consistent for abstract pairs (M = 81.66, SD = 9.77), compared with both associative pairs (M = 97.24, SD = 3.18; p = 0.0002, d = 2.15) and unrelated pairs (M = 89.98, SD = 9.22; p = 0.0331, d = 0.88). Opposed to the results of experiment 1, a trend towards a difference in consistency between associative pairs and unrelated pairs was found (p = 0.0772, d = 1.05). Again, there was no difference between the unrelated and novel unrelated conditions (M = 89.32, SD = 9.18; p = 0.996, d = 0.07).

Reaction times again revealed somewhat different patterns (Fig. 2E): though RTs were also affected by Relation type ($F(3, 45) = 5.97$, $p = 0.0208$, $\varepsilon = 0.40$, $\eta_p^2 = 0.28$), associative pairs (M = 0.61, SD = 0.17) evoked faster responses only compared to unrelated pairs (M = 0.90, SD = 0.45; p = 0.0079, d = 0.85), but not to abstract ones (M = 0.81, SD = 0.24; p = 0.0946, d = 0.97). Yet as in Experiment 1, abstract pairs did not differ from unrelated pairs (p = 0.7507, d = 0.24), and there was no difference between unrelated and novel unrelated pairs (M = 0.94, SD = 0.45; p = 0.9567, d = 0.10).

Subjects' ratings of relations' strength fully replicated Experiment 1 ($F(3, 45) = 621.79$, $p < 0.0001$, $\varepsilon = 0.43$, $\eta_p^2 = 0.98$; Fig. 2F), with associative pairs rated as most strongly related (M = 4.7, SD = 0.36), followed by abstract pairs (M = 4.08, SD = 0.56; p = 0.0002, d = 1.32, for the difference between associative and abstract) and unrelated pairs being rated as unrelated (M = 1.19, SD = 0.13; p = 0.0002, d = 12.82, for the comparison with associative pairs; p = 0.0002, d = 7.12, for the comparison with abstract ones). Again, no difference in ratings was found between the unrelated and the novel unrelated conditions (M = 1.18, SD = 0.15; p = 1, d = 0.05).

To compare subjects' performance in the two experiments, we conducted three post-hoc two-way ANOVAs for consistency, RT and strength score, with Relation type and Experiment as independent variables. A main effect of Experiment was found ($F(1, 15) = 12.18$, $p = 0.0033$, $\eta_p^2 = 0.45$) so that overall, subjects were more consistent in Experiment 1 (M = 94.33 SD = 5.36) than in Experiment 2 (M = 89.55 SD = 7.92). A main effect of Relation type was also found ($F(3, 45) = 22.29$, $p < 0.0001$, $\varepsilon = 0.44$, $\eta_p^2 = 0.60$). For RTs, the main effect of Experiment was marginal ($F(1, 15) = 3.38$, $p = 0.0858$, $\eta_p^2 = 0.18$) with a trend towards subjects being faster in Experiment 1 (mean RT = 0.64 SD = 0.08) than in Experiment 2 (mean RT = 0.81 SD = 0.24). Again, a main effect of Relation type was found ($F(3, 45) = 11.38$, $p = 0.0018$, $\varepsilon = 0.43$, $\eta_p^2 = 0.43$). For strength score, only a main effect of Relation type was found ($F(3, 45) = 1150.44$, $p < 0.0001$, $\varepsilon = 0.40$, $\eta_p^2 = 0.99$).

3.3.2. EEG results

In this experiment, the gradient of activations induced by the different relation types was evident, but was somewhat delayed and was differently distributed than in Experiment 1. This was again confirmed by the cluster-based permutation analysis, which showed a large cluster of activity (see Fig. 5). Surprisingly, despite the simultaneous presentation, a significant cluster differentiating between associative and unrelated pairs now started as early as about 200 ms, and the same goes for associative vs. abstract pairs (235 ms). Critically however, abstract and unrelated pairs were only differentiated at 425 ms. Thus, overall it seems that while associative pairs were detected relatively early, abstract ones remained largely undifferentiated from unrelated pairs, and only diverged from them in the middle of the N400 and later on during the late time window (note again that this does not indicate the latency or onset of the effects; Sassenhagen and Draschkow, 2019).

3.3.2.1. 300–500 time window. An ANOVA analysis with Region, Laterality and Relation type revealed a main effect for Relation type ($F(2, 30) = 15.92$, $p < 0.0001$, $\eta_p^2 = 0.51$), two-way interactions of Relation type and Laterality ($F(4, 60) = 4.11$, $p = 0.030$, $\varepsilon = 0.62$, $\eta_p^2 = 0.22$) and of Relation type and Area ($F(4, 60) = 11.79$, $p = 0.0003$, $\varepsilon = 0.53$, $\eta_p^2 = 0.44$), and finally the three-way interaction ($F(8, 120) = 2.49$, $p = 0.030$, $\eta_p^2 = 0.14$). The Tukey post-hoc tests confirmed that the pattern of activation in Experiment 2 was somewhat different from Experiment 1: while in Experiment 1, associative and abstract pairs differed mostly on left and middle sites and were largely undifferentiated on right ones, in Experiment 2, they were differentiated on all sites but the right PO (Table 5).

3.3.2.2. 500–700 time window. In the late window, a clear gradual pattern was observed across the scalp; A main effect for Relation type ($F(2, 30) = 460.68$, $p < 0.0001$, $\eta_p^2 = 0.62$), two-way interactions of Relation type and Laterality ($F(4, 60) = 7.93$, $p = 0.0032$, $\varepsilon = 0.58$,

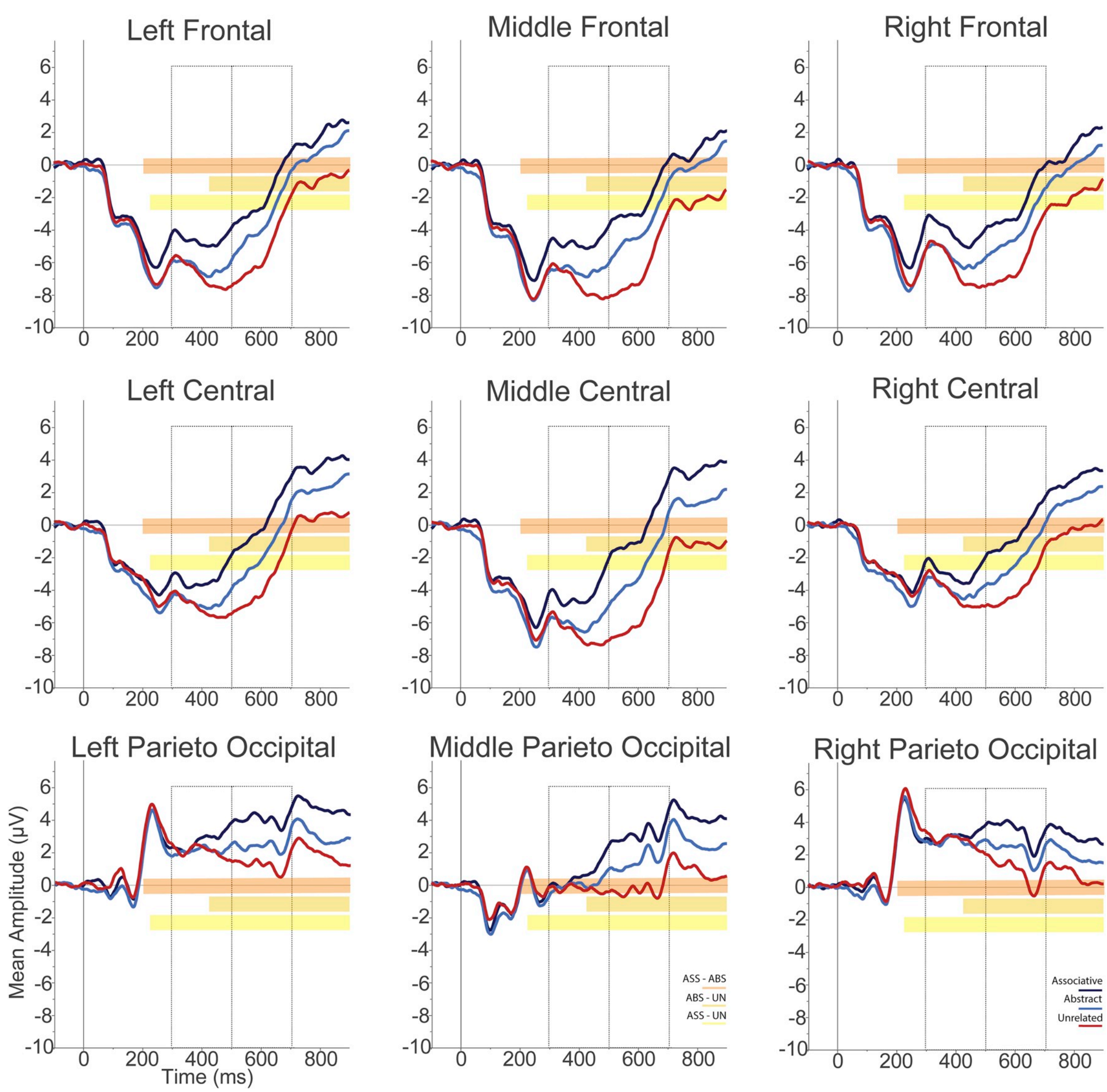

Fig. 5. Mean waveforms from Experiment 2 elicited by associative pairs (dark blue), abstract pairs (light blue), and unrelated pairs (red), for all regions. Light yellow patches indicate periods in which associative and unrelated pairs differed (as revealed by a cluster-based permutation analysis), light orange patches mark periods of significant difference between abstract and unrelated pairs, and darker orange patches indicate differences between associative and abstract pairs. The 300–500 ms and 500–700 ms time windows are framed with dotted lines. (See Supp-Figs. 5-1 for the filler condition). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 5
p values (top rows in each cell) and Cohen's d (bottom rows) for the post-hoc Tukey test conducted following the ANOVA on the 300–500 ms, for the three main contrasts, within each region.

	Frontal cites			Central cites			Parieto-occipital cites		
	Left	Middle	Right	Left	Middle	Right	Left	Middle	Right
Associative vs. Unrelated	p < 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002	n.s.
	d = 0.54	0.57	0.48	0.65	0.60	0.38	0.25	0.23	
Abstract vs. Unrelated	p = 0.0042	0.0002	0.0002	0.0246	0.0002	n.s.	n.s.	n.s.	n.s.
	d = 0.12	0.20	0.14	0.15	0.18				
Associative vs. Abstract	p < 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002	< 0.0002	n.s.
	d = 0.43	0.39	0.36	0.53	0.46	0.30	0.21	0.15	

$\eta_p^2 = 0.35$) and Relation type and Area ($F(4, 60) = 5.05$, $p = 0.0241$, $\varepsilon = 0.49$, $\eta_p^2 = 0.25$), as well as the three-way interaction were found ($F(8, 120) = 3.28$, $p = 0.0241$, $\varepsilon = 0.50$, $\eta_p^2 = 0.18$). Post-hoc Tukey tests (Table 6) revealed that associative and unrelated pairs, as well as abstract and unrelated pairs, differed in all nine areas, and the same was found for associative and abstract pairs.

The source of the interaction between Relation type and Laterality, which might have potentially indexed qualitative differences between the conditions, did not show any clear pattern. Rather, it stemmed from different responses in the different sites within each condition, with no clear pattern and very weak effect sizes: while for associative pairs, left sites differed from both middle and right ones ($p = 0.0168$, $d = 0.17$ and $p = 0.0038$, $d = 0.20$ respectively), for abstract pairs left sites only differed from middle ones ($p = 0.0004$, $d = 0.08$), and in unrelated pairs differences were found between both left and right sites to middle sites ($p = 0.0001$, $d = 0.07$ and $p = 0.0001$, $d = 0.06$ respectively). As these differences are very small in effect size and did not reveal any clear left-right patterns that align with the findings of Experiment 1, we do not discuss them any further.

3.3.2.3. Blocks analysis. Like in Experiment 1, we also inspected the data for each block separately (Fig. 6). A four-way ANOVA with Block, Region, Laterality and Relation type revealed an interaction of Relation type and Block ($F(2, 30) = 4.13$, $p = 0.0418$, $\eta_p^2 = 0.22$). Tukey tests revealed that this interaction stems from a change in processing of abstract pairs: while in the first block, they were undifferentiated from unrelated pairs ($p = 0.405$, $d = 0.32$) and different from associative pairs ($p = 0.0004$, $d = 0.81$), in the second block, they became undistinguished from associative pairs ($p = 0.833$, $d = 0.19$), and different from unrelated ones, yet with marginal significance ($p = 0.098$, $d = 0.44$). Note however that this analysis is conducted across areas (as the interaction did not involve Area/Laterality), which made it harder to find the differences between abstract and unrelated pairs in the first block, though they seem pronounced in visual inspection in frontal and central electrodes).

The cluster-based permutation analysis further confirmed that associative and abstract pairs differed only in block 1 (cluster onset: 202 ms), while abstract and unrelated pairs were differentiated both in block 1 and 2 (cluster onset: 468 ms and 497 ms correspondingly, uncorrected ($\alpha = 0.05$)). And so, the gradient of activation was accordingly mostly observed in block 1 (see significance patches in Fig. 6), and the graded N400 amplitude which was found when inspecting the data from the entire experiment actually resulted from averaging across block 1 and block 2. Importantly, here no qualitative differences were found: the ANOVA yielded a marginal interaction of Laterality, Relation type and Block ($F(4, 60) = 2.12$, $p = 0.09$, $\eta_p^2 = 0.12$), yet post-hoc Tukey tests did not reveal any pronounced difference between right and left sites (Table 7).

3.3.2.4. Eye movement analysis. In Experiment 2, the images were presented simultaneously in a manner that probably evoked eye movements, both at the saccades and the micro-saccades level. To make sure such effects do not drive the results, we defined a radial eye channel as the average over all 4 EOG channels, band-pass filtered to 30 and 100 Hz. Saccades were detected as any signal that diverted from the median of the radial channel by more than 2.5 standardized IQRs for more than 2 ms. We further defined that two consecutive saccades had to be at least 50 ms apart. Then, the number of saccades per condition was obtained, both during the entire epoch and the time preceding the critical time windows (i.e., the first 300 ms) (Keren et al., 2010; see also Croft and Barry, 2000; Elbert et al., 1985; Shan et al., 1995). During the first 300 ms, no differences in the number of saccades per condition were found ($F(2, 30) = 0.41$, $p = 0.6615$, $\varepsilon = 0.59$, $\eta_p^2 = 0.03$. Associative: $M = 0.85$, $SD = 0.08$; Abstract: $M = 0.86$, $SD = 0.08$; Unrelated: $M = 0.85$, $SD = 0.08$). The same (null) results were found when inspecting the entire epoch ($F(2, 30) = 0.44$, $p = 0.6644$, $\varepsilon = 0.57$, $\eta_p^2 = 0.03$. Associative: $M = 2.27$, $SD = 0.16$; Abstract: $M = 2.29$, $SD = 0.16$; Unrelated: $M = 2.27$, $SD = 0.15$). Thus, the difference between the conditions cannot be attributed to differential eye movements.

3.4. Discussion

Experiment 2 provided a multifaceted answer to the question evoked by the results of Experiment 1: do the findings represent genuine, general, differences in relational processing of abstract vs. associative relations, or are they specific to the sequential presentation of the pairs. The graded pattern observed in the N400 and Late negativity component was replicated here, with associative pairs eliciting the weakest amplitude, followed by abstract pairs and ending with the

Table 6
p values (top rows in each cell) and Cohen's d (bottom rows) for the post-hoc Tukey test conducted following the ANOVA on the 500–700 ms, for the three main contrasts, within each region.

	Frontal cites			Central cites			Parieto-occipital cites		
	Left	Middle	Right	Left	Middle	Right	Left	Middle	Right
Associative vs. Unrelated	p = 0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
	d = 0.77	0.76	0.65	1.24	1.21	0.99	0.81	0.90	0.74
Abstract vs. Unrelated	p = 0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
	d = 0.45	0.50	0.38	0.66	0.69	0.51	0.34	0.50	0.40
Associative vs. Abstract	p = 0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
	d = 0.42	0.34	0.32	0.73	0.67	0.51	0.44	0.41	0.34

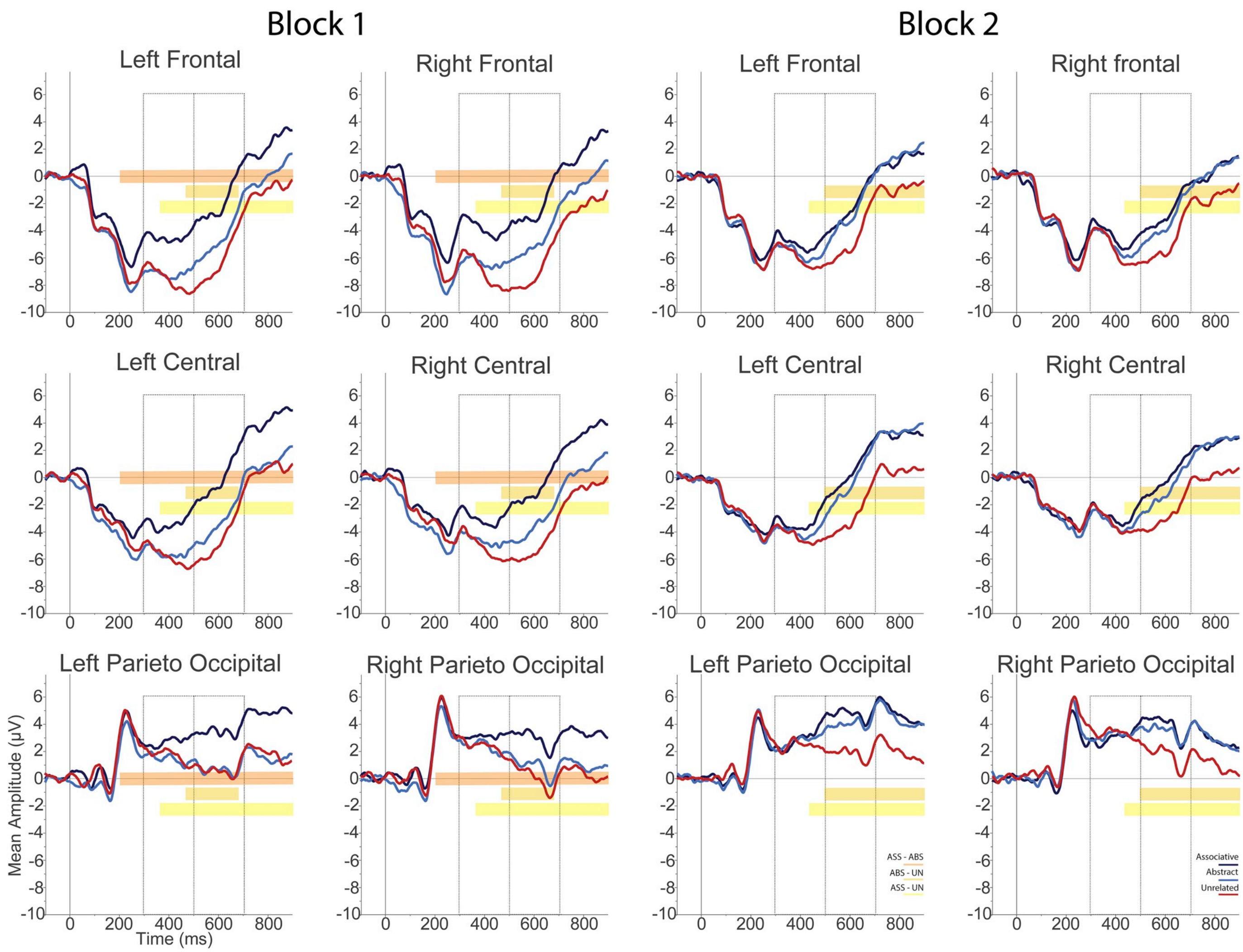

Fig. 6. Mean waveforms form Experiment 2 elicited by associative pairs (dark blue), abstract pairs (light blue), unrelated pairs (red), for left and right electrodes in block 1 and 2. Light yellow patches indicate periods in which associative and unrelated pairs differed (as revealed by a cluster-based permutation analysis), light orange patches mark periods of significant difference between abstract and unrelated pairs, and darker orange patches indicate differences between associative and abstract pairs. The 300–500 ms and 500–700 ms time windows are framed with dotted lines. (See Supp-Figs. 6-1 for the filler condition). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 7
p values (top rows in each cell) and Cohen's d (bottom rows) for the post-hoc Tukey test conducted following the ANOVA on the 300–700 ms, for the three way interaction, across regions, and in each block.

	Left	Middle	Right
BLOCK 1			
Associative vs. Unrelated	$p < 0.0002$	< 0.0002	< 0.0002
	$d = 1.17$	1.13	0.97
Abstract vs. Unrelated	$p = 0.02$	< 0.0002	< 0.0002
	$d = 0.24$	0.36	0.32
Associative vs. Abstract	$p < 0.0002$	< 0.0002	< 0.0002
	$d = 1.00$	0.78	0.11
BLOCK 2			
Associative vs. Unrelated	$p < 0.0002$	< 0.0002	< 0.0002
	$d = 0.69$	0.61	0.45
Abstract vs. Unrelated	$p < 0.0002$	< 0.0002	< 0.0002
	$d = 0.48$	0.49	0.32
Associative vs. Abstract	$p = 0.03$	0.005	0.096
	$d = 0.22$	0.19	0.16

unrelated pairs, yielding the most negative amplitude. However, this effect seems to rely on a differential response to the abstract pairs: these pairs seem to elicit a similar (yet not identical) response to unrelated pairs upon first exposure, and change to being indistinguishable from associative pairs on the second presentation. Critically, this transition was prominent here across all areas, while in Experiment 1 it was found only for left electrodes (while right electrodes differentiated between abstract and unrelated pairs from the start). Thus, the possible effect of laterality that emerged in Experiment 1 was not obtained using simultaneous presentation. This suggests that the source of this difference might lie in prediction generation, rather than in online relation processing of abstract vs. associative relations.

Experiment 2 further replicated the effect of repetition on the processing of abstract pairs, manifested in the effect of block on the waveforms; in both experiments, abstract pairs became largely undifferentiated from associative pairs in block 2. This pattern cannot simply be explained by a repetition effect (e.g., Bentin and McCarthy, 1994; Besson et al., 1992; Van Petten and Senkfor, 1996) where the amplitude of N400 or the Late negativity is reduced upon repetition of stimuli, because such repetition effects should have also been observed for the other conditions too. And this was not the case in our experiment. Hence, there might have been some unique learning processes, occurring only for the abstract pairs. In that respect, our results echo those reported for novel metaphors (Goldstein et al., 2012): after subjects were requested to explain novel metaphors, a smaller, less negative N400 amplitude was found, similar to that evoked by conventional metaphors (see also General Discussion below).

4. General discussion

In this study, we set to examine associative and abstract relational processing, asking if they rest on the same neural mechanisms – differing quantitatively only by the difficulty of processing attempts – or are mediated by qualitatively different processes, possibly one that is based more on statistical learning (Pulvermüller, 2013), and another that is more integrative, relying on broader semantic fields (Beeman et al., 1994; Jung-Beeman, 2005) and conceivably also more metaphorical thinking (Holyoak and Stamenković, 2018). Our results support the former account, as a graded pattern of activation was found in the two experiments, both for the N400 and for the Late negativity components.

Notably, in Experiment 1 we also found initial support for a qualitative difference, which was manifested as a difference in the distribution of the effect: in the first block, left sites did not distinguish abstract from unrelated pairs, while right sites did. One might be prone to suggest that this qualitative difference possibly reflects how the two hemispheres could be differently involved in deciphering associative vs. abstract relations. Yet our laterality differences are merely differences in *scalp* distributions, that do not necessarily reflect similarly lateralized *generators.* In fact, such scalp distributions might sometimes represent the exact opposite pattern, with underlying contralateral generators (for discussion, see Van Petten and Luka, 2006; Swick et al., 1994; Lau et al., 2008). Thus, future studies are needed to directly examine the potentially different roles of the two hemispheres in associative vs. abstract processing, for example by using a split-visual field presentation (Bourne, 2006). Most importantly, because this laterality effect was not found in Experiment 2, it is more likely that it represents processes that are uniquely evoked by the sequential presentation, like violations of expectation (Summerfield and De Lange, 2014; Trapp and Bar, 2015). Thus, when taken together, our results imply that while there might be two mechanisms that differ in prediction generation, online relation processing of associative vs. abstract relations seems to be mediated by a single system that is activated to a different degree for each relation type.

Importantly, the graded pattern of activation that supports the quantitative account was also found to stem from a more intricate pattern than we expected. When the data of both experiments was collapsed across blocks, a clear graded pattern of activation was found: unrelated pairs elicited the most negative amplitude followed by abstract related pairs and finally by associative related pairs (cf. McPherson and Holcomb, 1999). But, in fact, this graded pattern was only obtained in the first blocks in both experiments (in Experiment 1, in right sites; in Experiment 2, independent of laterality). In the second block, the waveforms seemed to diverge dichotomously with both relation types differing from unrelated pairs. And so, what we found was more similar to a dichotomous 'related vs. unrelated' pattern in the second block in both experiments. Abstract pairs switched from evoking waveforms that are more similar (though not identical) to the unrelated condition in the first block, to waveforms that are almost indistinguishable from the associative related condition in the second block.

This switching might be explained by a "conventionalization" process, which occurs only for the abstract pairs, since only in these pairs a novel meaning - comprised of very distant concepts – must be established in order to correctly judge the relation. This accords with the 'career of a metaphor model' (Bowdle and Gentner, 2005), which claims that metaphors undergo a gradual and quantitatively measurable process (note that our pairs were not created as examples for metaphors per se, yet deciphering their relations might have involved some metaphorical thinking). A novel metaphor begins as a novel relational comparison, requiring an effortful integration of an inference from a base word to a target word from two distinct and far semantic fields. With time, a novel metaphor might become conventional, accessed in parallel to the literal meaning, with no more effort or processing time. Indeed, several ERP studies have shown a graded N400 amplitude, similar to that found in our experiments, in which novel metaphors elicited the most negative amplitude, conventional metaphors an intermediate amplitude and literal sentences the smallest N400 amplitude (Arzouan et al., 2007; Coulson and Van Petten, 2002; De Grauwe et al., 2010; Goldstein et al., 2012; Mashal and Faust, 2009; see also Lai and Curran, 2013, which found a similar N400 reduction by inducing mapping mindsets which facilitated computing of either novel or conventional meaning). Akin to our findings, this N400 was followed by a similarly graded Late Negativity component, reminiscent of findings in words (Friederici et al., 1999) and metaphors (Rutter et al., 2012), sometimes interacting with LPC amplitudes for novel meanings as seen in previous metaphors studies (De Grauwe et al., 2010; Coulson and Van Petten, 2002; Yang et al., 2013). Both late components are held to represent the extended effort to integrate pairs that might initially seem unrelated, but are then integrated so to form a novel meaning.

Aside from understanding relational processing, our findings are also of importance to the ongoing debate about the functional meaning of the N400 component. Our results suggest that with sequential presentation, at least two distinct mechanisms underlie the observed N400 amplitude, namely the process of integration (e.g., Brown and Hagoort, 1993; Friederici et al., 1999; Baggio and Hagoort, 2011) or ease of retrieval (e.g., Kutas and Federmeier, 2011; Lau et al., 2008) and that of prediction, or expectation violation given that the images in the pair were presented one after another (Federmeier and Kutas, 1999, 2001; 2002; Federmeier, 2007). When presentation was sequential (Experiment 1), we observed differences in the distribution of the gradual N400 effect, which might be attributed to differences in prediction mechanisms. In line with this interpretation, presenting the image pairs in parallel rather than sequentially (Experiment 2), eliminated the laterality differences observed in the first experiment. Thus, it seems that N400 partially reflects prediction generation and expectation violations (Metusalem et al., 2016; Federmeier, 2007). These come into play when a cue is presented, leading to the formation of specific predictions, yet even when such expectations are not formed in advance (i.e., when the two images are simultaneously presented) N400 is clearly modulated by relation type; in that case, it seems like integration difficulty (Brown and Hagoort, 1993; McPherson and Holcomb, 1999; Kutas and Van Petten, 1994) or level of access (Kutas and Federmeier, 2011; Lau et al., 2008; Arzouan et al., 2007; De Grauwe et al., 2010) might drive the effect.

When interpreting the results, one should however bear in mind that in our experiments, relation strength and relation type were correlated. Since we defined abstract relations as those that are not based on co-occurrence, our abstract pairs were often less strongly related than associative ones, and probably less familiar. This inherent difference might have overshadowed a potential qualitative difference between the two types of relations. Hence, in order to fully support a quantitative account, future studies should use abstract pairs that are strongly related (e.g., a lion and a crown), and/or associative pairs that are weakly related (e.g., a fork and a pot) in order to equate relation strength.

To conclude, the results of two EEG experiments suggest that a single mechanism accounts for associative and abstract relational processing, as implied by a gradual modulation of the N400 and the Late Negativity components. Thus, our ability to decipher relations between concepts seems to rest on similar mechanisms, whether these relations are based on daily co-occurrences or on more abstract, conceptual connections. Yet when it comes to forming predictions, there seems to be unique mechanisms for the two types of relations: one mechanism, indexed here by activity in left electrodes, seems to generate more closed-end predictions, as opposed to a potentially different mechanism, indexed here by activity in right electrodes, which is more open-ended. Hence, relations processing seems to change shape and form as a function of the way these relations are revealed to the observer. Both prediction-based mechanisms and semantic-knowledge retrieval and integration mechanisms underlie our remarkable ability to grasp relations of different types, so to promote our understanding of others and of our environment.

CRediT authorship contribution statement

Leemor Zucker: Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing - original draft. **Liad Mudrik:** Conceptualization, Funding acquisition, Methodology, Resources, Software, Supervision, Validation, Writing - review & editing.

Acknowledgements

The study was funded by the Israel Science Foundation (grant No. 1847/16). We wish to thank Maya Gotlieb for assisting with data collection. Uri Korisky and Alyssa Truman for assisting with data processing. Amir Tal, Aya Meltzer-Asscher, Orna Peleg and Einat Shetreet for providing comments and suggestions during proofreading.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2019.107127.

References

Arzouan, Y., Goldstein, A., Faust, M., 2007. Brainwaves are stethoscopes: ERP correlates of novel metaphor comprehension. Brain Res. 1160, 69–81 .
Badre, D., D'esposito, M., 2009. Is the rostro-caudal axis of the frontal lobe hierarchical? Nat. Rev. Neurosci. 10 (9), 659.
Baggio, G., Hagoort, P., 2011. The balance between memory and unification in semantics: a dynamic account of the N400. Lang. Cogn. Process. 26 (9), 1338–1367.
Bar, M., 2004. Visual objects in context. Nat. Rev. Neurosci. 5 (8), 617–629 .
Barrett, S.E., Rugg, M.D., 1990. Event-related potentials and the semantic matching of pictures. Brain Cogn. 14 (2), 201–212 .
Beeman, M., Friedman, R.B., Grafman, J., Perez, E., Diamond, S., Lindsay, M.B., 1994. Summation priming and coarse semantic coding in the right hemisphere. J. Cogn. Neurosci. 6 (1), 26–45 .
Benjamini, Y., Drai, D., Elmer, G., Kafkafi, N., Golani, I., 2001. Controlling the false discovery rate in behavior genetics research. Behav. Brain Res. 125 (1–2), 279–284.
Benjamini, Y., Hochberg, Y., 2000. On the adaptive control of the false discovery rate in multiple testing with independent statistics. J. Educ. Behav. Stat. 25 (1), 60–83 .
Bentin, S., McCarthy, G., 1994. The effects of immediate stimulus repetition on reaction time and event-related potentials in tasks of different complexity. J. Exp. Psychol. Learn. Mem. Cogn. 20 (1), 130.
Besson, M., Kutas, M., Petten, C.V., 1992. An event-related potential (ERP) analysis of semantic congruity and repetition effects in sentences. J. Cogn. Neurosci. 4 (2), 132–149.
Bornkessel-Schlesewsky, I., Kretzschmar, F., Tune, S., Wang, L., Genç, S., Philipp, M., et al., 2011. Think globally: cross-linguistic variation in electrophysiological activity during sentence comprehension. Brain Lang. 117 (3), 133–152.
Bowdle, B.F., Gentner, D., 2005. The career of metaphor. Psychol. Rev. 112 (1), 193.
Bourne, V.J., 2006. The divided visual field paradigm: methodological considerations. Laterality 11 (4), 373–393 .
Brainard, D.H., Vision, S., 1997. The psychophysics toolbox. Spatial Vis. 10, 433–436 .
Brouwer, H., Fitz, H., Hoeks, J., 2012. Getting real about semantic illusions: rethinking the functional role of the P600 in language comprehension. Brain Res. 1446, 127–143.
Brown, C., Hagoort, P., 1993. The processing nature of the N400: evidence from masked priming. J. Cogn. Neurosci. 5 (1), 34–44 .
Cardillo, E.R., Watson, C.E., Schmidt, G.L., Kranjec, A., Chatterjee, A., 2012. From novel to familiar: tuning the brain for metaphors. Neuroimage 59 (4), 3212–3221 .
Cho, S., Moody, T.D., Fernandino, L., Mumford, J.A., Poldrack, R.A., Cannon, T.D., Knowlton, B.J., Holyoak, K.J., 2009. Common and dissociable prefrontal loci associated with component mechanisms of analogical reasoning. Cerebr. Cortex 20 (3), 524–533 .
Christoff, K., Keramatian, K., Gordon, A.M., Smith, R., Mädler, B., 2009. Prefrontal organization of cognitive control according to levels of abstraction. Brain Res. 1286, 94–105.
Cohn, N., Kutas, M., 2015. Getting a cue before getting a clue: event-related potentials to inference in visual narrative comprehension. Neuropsychologia 77, 267–278 .
Collins, A.M., Loftus, E.F., 1975. A spreading-activation theory of semantic processing. Psychol. Rev. 82 (6), 407.
Coulson, S., King, J., Kutas, M., 1998. Expect the unexpected: event-related brain response to morphosyntactic violations. Lang. Cogn. Process. 13 (1), 21–58.
Coulson, S., Van Petten, C., 2002. Conceptual integration and metaphor: an event-related potential study. Mem. Cogn. 30 (6), 958–968 .
Coulson, S., Van Petten, C., 2007. A special role for the right hemisphere in metaphor comprehension?: ERP evidence from hemifield presentation. Brain Res. 1146, 128–145.
Cousineau, D., 2005. Confidence intervals in within-subject designs: a simpler solution to Loftus and Masson's method. Tutorials Quant. Methods Psychol. 1 (1), 42–45 .
Croft, R.J., Barry, R.J., 2000. Removal of ocular artifact from the EEG: a review. Neurophysiologie Clinique/Clin. Neurophysiol. 30 (1), 5–19 .
De Grauwe, S., Swain, A., Holcomb, P.J., Ditman, T., Kuperberg, G.R., 2010. Electrophysiological insights into the processing of nominal metaphors. Neuropsychologia 48 (7), 1965–1984 .
DeLong, K.A., Quante, L., Kutas, M., 2014. Predictability, plausibility, and two late ERP positivities during written sentence comprehension. Neuropsychologia 61, 150–162 .
Donchin, E., 1981. Surprise!… surprise? Psychophysiology 18 (5), 493–513.
Doumas, L.A., Hummel, J.E., Sandhofer, C.M., 2008. A theory of the discovery and predication of relational concepts. Psychol. Rev. 115 (1), 1 .
Elbert, T., Lutzenberger, W., Rockstroh, B., Birbaumer, N., 1985. Removal of ocular artifacts from the EEG—a biophysical approach to the EOG. Clin. Neurophysiol. 60 (5), 455–463 .
Faul, F., Erdfelder, E., Lang, A.G., Buchner, A., 2007. G* Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav. Res. Methods 39 (2), 175–191 .
Federmeier, K.D., 2007. Thinking ahead: the role and roots of prediction in language comprehension. Psychophysiology 44 (4), 491–505 .
Federmeier, K.D., Kutas, M., 1999. Right words and left words: electrophysiological evidence for hemispheric differences in meaning processing. Cogn. Brain Res. 8 (3), 373–392 .
Federmeier, K.D., Kutas, M., 2001. Meaning and modality: influences of context, semantic memory organization, and perceptual predictability on picture processing. J. Exp. Psychol. Learn. Mem. Cogn. 27 (1), 202–224 .
Federmeier, K.D., Kutas, M., 2002. Picture the difference: electrophysiological investigations of picture processing in the two cerebral hemispheres. Neuropsychologia 40 (7), 730–747 .
Forceville, C., 2007. Multimodal metaphor in ten Dutch TV commercials. Public J. Semiot. 1, 19–51.
Friederici, A.D., Steinhauer, K., Frisch, S., 1999. Lexical integration: sequential effects of syntactic and semantic information. Mem. Cogn. 27 (3), 438–453 .
Frishkoff, G.A., 2007. Hemispheric differences in strong versus weak semantic priming: evidence from event-related brain potentials. Brain Lang. 100 (1), 23–43.
Ganis, G., Kutas, M., Sereno, M.I., 1996. The search for “common sense”: an electrophysiological study of the comprehension of words and pictures in reading. J. Cogn. Neurosci. 8 (2), 89–106.
Gentner, D., 1983. Structure-mapping: a theoretical framework for analogy. Cogn. Sci. 7 (2), 155–170 .
Gentner, D., 2010. Bootstrapping the mind: analogical processes and symbol systems. Cogn. Sci. 34 (5), 752–775 .
Gentner, D., 2016. Language as cognitive tool kit: how language supports relational thought. Am. Psychol. 71 (8), 650.
Gentner, D., Namy, L.L., 2006. Analogical processes in language learning. Curr. Dir. Psychol. Sci. 15 (6), 297–301.
Goldstein, A., Arzouan, Y., Faust, M., 2012. Killing a novel metaphor and reviving a dead one: ERP correlates of metaphor conventionalization. Brain Lang. 123 (2), 137–142 .
Goodwin, G.P., Johnson-Laird, P.N., 2005. Reasoning about relations. Psychol. Rev. 112 (2), 468.
Greenhouse, S.W., Geisser, S., 1959. On methods in the analysis of profile data. Psychometrika 24 (2), 95–112 .
Gronau, N., Neta, M., Bar, M., 2008. Integrated contextual representation for objects' identities and their locations. J. Cogn. Neurosci. 20 (3), 371–388 .
Hagoort, P., Brown, C., 1994. Brain responses to lexical ambiguity resolution and parsing. Perspect. Sentence Process. 45–80.
Halford, G.S., Bain, J.D., Maybery, M.T., Andrews, G., 1998. Induction of relational schemas: common processes in reasoning and complex learning. Cogn. Psychol. 35 (3), 201–245 .
Halford, G.S., Wilson, W.H., Phillips, S., 2010. Relational knowledge: the foundation of higher cognition. Trends Cognit. Sci. 14 (11), 497–505 .
Holcomb, P.J., Mcpherson, W.B., 1994. Event-related brain potentials reflect semantic priming in an object decision task. Brain Cogn. 24 (2), 259–276.
Holyoak, K.J., Stamenković, D., 2018. Metaphor comprehension: a critical review of theories and evidence. Psychol. Bull. 144 (6), 641–671.
Hummel, J.E., Holyoak, K.J., 2003. A symbolic-connectionist theory of relational inference and generalization. Psychol. Rev. 110 (2), 220.
Indurkhya, B., Ojha, A., 2017. Interpreting visual metaphors: asymmetry and reversibility. Poetics Today 38 (1), 93–121 .
Jung, T.P., Makeig, S., Westerfield, M., Townsend, J., Courchesne, E., Sejnowski, T.J., 2000. Removal of eye activity artifacts from visual event-related potentials in normal and clinical subjects. Clin. Neurophysiol. 111 (10), 1745–1758 .
Jung-Beeman, M., 2005. Bilateral brain processes for comprehending natural language. Trends Cognit. Sci. 9 (11), 512–518 .
Keppel, G., Postman, L.J. (Eds.), 1970. Norms of Word Association. Academic Press.
Keren, A.S., Yuval-Greenberg, S., Deouell, L.Y., 2010. Saccadic spike potentials in gamma-band EEG: characterization, detection and suppression. Neuroimage 49 (3), 2248–2263 .
King, J.W., Kutas, M., 1995. Who did what and when? Using word-and clause-level ERPs to monitor working memory usage in reading. J. Cogn. Neurosci. 7 (3), 376–395.

Krawczyk, D.C., McClelland, M.M., Donovan, C.M., Tillman, G.D., Maguire, M.J., 2010. An fMRI investigation of cognitive stages in reasoning by analogy. Brain Res. 1342, 63–73.
Kroger, J.K., Holyoak, K.J., Hummel, J.E., 2004. Varieties of sameness: the impact of relational complexity on perceptual comparisons. Cogn. Sci. 28 (3), 335–358 .
Kuperberg, G.R., 2007. Neural mechanisms of language comprehension: challenges to syntax. Brain Res. 1146, 23–49.
Kutas, M., Federmeier, K.D., 2011. Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). Annu. Rev. Psychol. 62, 621–647 .
Kutas, M., Hillyard, S.A., 1980a. Event-related brain potentials to semantically inappropriate and surprisingly large words. Biol. Psychol. 11 (2), 99–116 .
Kutas, M., Hillyard, S.A., 1980b. Reading senseless sentences: brain potentials reflect semantic incongruity. Science 207 (4427), 203–205.
Kutas, M., Hillyard, S.A., 1984. Event-related brain potentials (ERPs) elicited by novel stimuli during sentence processinga. Ann. N. Y. Acad. Sci. 425 (1), 236–241 .
Kutas, M., Hillyard, S.A., Gazzaniga, M.S., 1988. Processing of semantic anomaly by right and left hemispheres of commissurotomy patients: evidence from event-related brain potentials. Brain 111 (3), 553–576.
Kutas, M., Van Petten, C., 1994. Psycholinguistics Electrified. Handbook of Psycholinguistics. , pp. 83–143.
Lai, V.T., Curran, T., 2013. ERP evidence for conceptual mappings and comparison processes during the comprehension of conventional and novel metaphors. Brain Lang. 127 (3), 484–496 .
Lakoff, G., 1993. The Contemporary Theory of Metaphor.
Lau, E.F., Holcomb, P.J., Kuperberg, G.R., 2013. Dissociating N400 effects of prediction from association in single-word contexts. J. Cogn. Neurosci. 25 (3), 484–502 .
Lau, E.F., Phillips, C., Poeppel, D., 2008. A cortical network for semantics:(de) constructing the N400. Nat. Rev. Neurosci. 9 (12), 920.
Luck, S.J., 2014. An Introduction to the Event-Related Potential Technique. MIT press.
Luck, S.J., Girelli, M., 1998. Electrophysiological Approaches to the Study of Selective Attention in the Human Brain.
Maris, E., Oostenveld, R., 2007. Nonparametric statistical testing of EEG-and MEG-data. J. Neurosci. Methods 164 (1), 177–190 .
Mashal, N., Faust, M., 2009. Conventionalisation of novel metaphors: a shift in hemispheric asymmetry. Laterality 14 (6), 573–589 .
Mashal, N., Faust, M., Hendler, T., Jung-Beeman, M., 2007. An fMRI investigation of the neural correlates underlying the processing of novel metaphoric expressions. Brain Lang. 100 (2), 115–126.
McNamara, T.P., 1992. Theories of priming: I. Associative distance and lag. J. Exp. Psychol. Learn. Mem. Cogn. 18 (6), 1173.
McPherson, W.B., Holcomb, P.J., 1999. An electrophysiological investigation of semantic priming with pictures of real objects. Psychophysiology 36 (1), 53–65 .
Mecklinger, A., Pfeifer, E., 1996. Event-related potentials reveal topographical and temporal distinct neuronal activation patterns for spatial and object working memory. Cogn. Brain Res. 4 (3), 211–224.
Morey, R.D., 2008. Confidence intervals from normalized data: a correction to Cousineau (2005). Reason 4 (2), 61–64 .
Metusalem, R., Kutas, M., Urbach, T.P., Elman, J.L., 2016. Hemispheric asymmetry in event knowledge activation during incremental language comprehension: a visual half-field ERP study. Neuropsychologia 84, 252–271 .
Mudrik, L., Lamy, D., Deouell, L.Y., 2010. ERP evidence for context congruity effects during simultaneous object–scene processing. Neuropsychologia 48 (2), 507–517 .
Mudrik, L., Shalgi, S., Lamy, D., Deouell, L.Y., 2014. Synchronous contextual irregularities affect early scene processing: replication and extension. Neuropsychologia 56, 447–458.
Neely, J.H., 1977. Semantic priming and retrieval from lexical memory: roles of inhibitionless spreading activation and limited-capacity attention. J. Exp. Psychol. Gen. 106 (3), 226.
Neely, J.H., Keefe, D.E., Ross, K.L., 1989. Semantic priming in the lexical decision task: roles of prospective prime-generated expectancies and retrospective semantic matching. J. Exp. Psychol. Learn. Mem. Cogn. 15 (6), 1003.
Ness, T., Meltzer-Asscher, A., 2018. Lexical inhibition due to failed prediction: behavioral evidence and ERP correlates. J. Exp. Psychol. Learn. Mem. Cogn. 44, 1269–1285.
Nieuwland, M., Barr, D., Bartolozzi, F., Busch-Moreno, S., Donaldson, D., Ferguson, H.J.,, et al., 2019. Dissociable Effects of Prediction and Integration during Language Comprehension: Evidence from a Large-Scale Study Using Brain Potentials. Proceedings of the Royal Society B: Biological Sciences (in press).
Ortiz, M.J., 2011. Primary metaphors and monomodal visual metaphors. J. Pragmat. 43 (6), 1568–1580 .
Ortiz, M.J., Grima Murcia, M.D., Fernandez, E., 2017. Brain Processing of Visual Metaphors: an Electrophysiological Study. .
Pelli, D.G., 1997. The VideoToolbox software for visual psychophysics: transforming numbers into movies. Spatial Vis. 10 (4), 437–442 .
Picton, T.W., Bentin, S., Berg, P., Donchin, E., Hillyard, S.A., Johnson, R., Taylor, M.J., 2000. Guidelines for using human event-related potentials to study cognition: recording standards and publication criteria. Psychophysiology 37 (2), 127–152 .
Plaut, D.C., 1995. Double dissociation without modularity: evidence from connectionist neuropsychology. J. Clin. Exp. Neuropsychol. 17 (2), 291–321.
Pulvermüller, F., 2013. How neurons make meaning: brain mechanisms for embodied and abstract-symbolic semantics. Trends Cognit. Sci. 17 (9), 458–470 .
Rapp, A.M., Mutschler, D.E., Erb, M., 2012. Where in the brain is nonliteral language? A coordinate-based meta-analysis of functional magnetic resonance imaging studies. Neuroimage 63 (1), 600–610.
Rataj, K., Przekoracka-Krawczyk, A., van der Lubbe, R.H., 2018. On understanding creative language: the late positive complex and novel metaphor comprehension. Brain Res. 1678, 231–244 .
Ruchkin, D.S., Johnson Jr., R., Grafman, J., Canoune, H., Ritter, W., 1992. Distinctions and similarities among working memory processes: an event-related potential study. Cogn. Brain Res. 1 (1), 53–66.
Rutter, B., Kröger, S., Hill, H., Windmann, S., Hermann, C., Abraham, A., 2012. Can clouds dance? Part 2: an ERP investigation of passive conceptual expansion. Brain Cogn. 80 (3), 301–310 .
Sassenhagen, J., Draschkow, D., 2019. Cluster-based permutation tests of MEG/EEG data do not establish significance of effect latency or location. Psychophysiology, e13335.
Sassenhagen, J., Schlesewsky, M., Bornkessel-Schlesewsky, I., 2014. The P600-as-P3 hypothesis revisited: single-trial analyses reveal that the late EEG positivity following linguistically deviant material is reaction time aligned. Brain Lang. 137, 29–39.
Schmidt, G.L., Kranjec, A., Cardillo, E.R., Chatterjee, A., 2010. Beyond laterality: a critical assessment of research on the neural basis of metaphor. J. Int. Neuropsychol. Soc. 16 (1), 1–5.
Schmidt, G.L., Seger, C.A., 2009. Neural correlates of metaphor processing: the roles of figurativeness, familiarity and difficulty. Brain Cogn. 71 (3), 375–386.
Schneider, S., Rapp, A.M., Haeußinger, F.B., Ernst, L.H., Hamm, F., Fallgatter, A.J., Ehlis, A.C., 2014. Beyond the N400: complementary access to early neural correlates of novel metaphor comprehension using combined electrophysiological and haemodynamic measurements. Cortex 53, 45–59.
Shan, Y., Moster, M.L., Roemer, R.A., 1995. The effects of time point alignment on the amplitude of averaged orbital presaccadic spike potential (SP). Electroencephalogr. Clin. Neurophysiol. 95 (6), 475–477 .
Speed, A., 2010. Abstract relational categories, graded persistence, and prefrontal cortical representation. .
Spellman, B.A., Holyoak, K.J., Morrison, R.G., 2001. Analogical priming via semantic relations. Mem. Cogn. 29 (3), 383–393 .
Steinhauer, K., Drury, J.E., Portner, P., Walenski, M., Ullman, M.T., 2010. Syntax, concepts, and logic in the temporal dynamics of language comprehension: evidence from event-related potentials. Neuropsychologia 48 (6), 1525–1542.
Stringaris, A.K., Medford, N.C., Giampietro, V., Brammer, M.J., David, A.S., 2007. Deriving meaning: distinct neural mechanisms for metaphoric, literal, and non-meaningful sentences. Brain Lang. 100 (2), 150–162.
Summerfield, C., De Lange, F.P., 2014. Expectation in perceptual decision making: neural and computational mechanisms. Nat. Rev. Neurosci. 15 (11), 745.
Sutton, S., Braren, M., Zubin, J., John, E.R., 1965. Evoked-potential correlates of stimulus uncertainty. Science 150 (3700), 1187–1188.
Swick, D., Kutas, M., Neville, H.J., 1994. Localizing the neural generators of event-related brain potentials. Localization and neuroimaging in neuropsychology. Found. Neuropsychol. 73–121 .
Thompson-Schill, S.L., Kurtz, K.J., Gabrieli, J.D., 1998. Effects of semantic and associative relatedness on automatic priming. J. Mem. Lang. 38 (4), 440–458.
Trapp, S., Bar, M., 2015. Prediction, context, and competition in visual recognition. Ann. N. Y. Acad. Sci. 1339 (1), 190–198 .
Tversky, A., 1977. Features of similarity. Psychol. Rev. 84 (4), 327.
Van de Meerendonk, N., Kolk, H.H., Chwilla, D.J., Vissers, C.T.W., 2009. Monitoring in language perception. Lang. Linguist. Compass 3 (5), 1211–1224.
Van Petten, C., Luka, B.J., 2006. Neural localization of semantic context effects in electromagnetic and hemodynamic studies. Brain Lang. 97 (3), 279–293 .
Van Petten, C., Luka, B.J., 2012. Prediction during language comprehension: benefits, costs, and ERP components. Int. J. Psychophysiol. 83 (2), 176–190 .
Van Petten, C., Senkfor, A.J., 1996. Memory for words and novel visual patterns: repetition, recognition, and encoding effects in the event-related brain potential. Psychophysiology 33 (5), 491–506.
Vendetti, M.S., Bunge, S.A., 2014. Evolutionary and developmental changes in the lateral frontoparietal network: a little goes a long way for higher-level cognition. Neuron 84 (5), 906–917 .
Weiland, H., Bambini, V., Schumacher, P.B., 2014. The role of literal meaning in figurative language comprehension: evidence from masked priming ERP. Front. Hum. Neurosci. 8, 583.
Wilson, S.M., Galantucci, S., Tartaglia, M.C., Gorno-Tempini, M.L., 2012. The neural basis of syntactic deficits in primary progressive aphasia. Brain Lang. 122 (3), 190–198.
Yang, F.P.G., Bradley, K., Huq, M., Wu, D.L., Krawczyk, D.C., 2013. Contextual effects on conceptual blending in metaphors: an event-related potential study. J. Neurolinguistics 26 (2), 312–326.