Spatial distance effects on incremental semantic interpretation of abstract sentences: Evidence

from eye tracking[1]

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[1] The data presented in this manuscript were also reported in the form of a thesis in partial fulfilment of the requirements to obtain a doctoral degree (EG).

Abstract

A large body of evidence has shown that visual context information can rapidly modulate language comprehension for concrete sentences and when it is mediated by a referential or a lexical-semantic link. What has not yet been examined is whether visual context can also modulate comprehension of abstract sentences incrementally when it is neither referenced by, nor lexically associated with, the sentence. Three eye-tracking reading experiments examined the effects of spatial distance between words (Experiment 1) and objects (Experiment 2 and 3) on participants' reading times for sentences that convey similarity or difference between two abstract nouns (e.g., *Peace and war are certainly different…*). Before reading the sentence, participants inspected a visual context with two playing cards that moved either far apart or close together. In Experiment 1, the cards turned and showed the first two nouns of the sentence (e.g., *peace*, *war*). In Experiments 2 and 3, they turned but remained blank. Participants' reading times at the adjective (Experiment 1: first-pass reading time; Experiment 2: total times) and at the second noun phrase (Experiment 3: first-pass times) were faster for sentences that expressed similarity when the preceding words/objects were close together (vs. far apart) and for sentences that expressed dissimilarity when the preceding words/objects were far apart (vs. close together). Thus, spatial distance between words or entirely unrelated objects can rapidly and incrementally modulate the semantic interpretation of abstract sentences.

Keywords: Abstract sentences, spatial distance, visual context, reading, eye tracking.

1.1. Visual information and the comprehension of concrete language

More than a decade after Tanenhaus, Spivey-Knowlton, Eberhard and Sedivy (1995) reported rapid visual context effects on syntactic structuring during spoken language comprehension, the cognitive sciences abound with eye-tracking research into how real-time language comprehension relates to visual perceptual processes (e.g., Ferreira, Apel, & Henderson, 2008; Hartsuiker, Huettig, & Olivers, 2011; Richardson, Altmann, Spivey, & Hoover, 2009 for relevant discussion). For concrete language, eye-tracking evidence suggests that referential visual context can inform incremental semantic interpretation (Sedivy, Tanenhaus, Chambers & Carlson, 1999) as well as syntactic structuring (Tanenhaus et al., 1995); that experienced-based object affordances can guide structural disambiguation (e.g., Chambers, Tanenhaus & Magnuson, 2004); and that depicted clipart events can disambiguate locally syntactically ambiguous utterances (e.g., Knoeferle, Crocker, Scheepers & Pickering, 2005; Knoeferle & Crocker, 2006). In addition, action-verb incongruence can rapidly modulate sentence comprehension during reading (Knoeferle, Urbach, & Kutas, 2011). In all of these studies, objects and actions in visual context were referenced by language.

A number of eye-tracking studies have furthermore shown that objects which are not mentioned but which are semantically related to a target word attract more visual attention than semantically unrelated objects (e.g., Huettig & Altmann, 2005; Huettig, Quinlan, McDonald & Altmann, 2006; Mirman & Magnuson, 2009); that phonological competitors (words that begin with the same syllable as the target) compete for attention with the target during early stages of referential processing (Allopenna, Magnuson, & Tanenhaus, 1998); and that more visual attention goes to objects that share the color or shape of a target referent than to unrelated objects (see Dahan & Tanenhaus, 2005; Huettig & McQueen, 2007; Huettig & Altmann, 2011). In sum,

visual context can rapidly interact with the real-time comprehension of concrete language in the presence of a referential (a word refers to an object) or lexical-semantic (a word is semantically associated with an object) link.

In parallel, it has been found that other visual features can modulate language processing even when they are not explicitly mentioned but implied by language (e.g., Kaschak et al., 2005; Meteyard, Zokaei, Bahrami, & Vigliocco, 2008; Pecher, van Dantzig, Zwaan & Zeelenberg, 2009; Stanfield & Zwaan, 2001; Zwaan, Stanfield, & Yaxley, 2002). In a picture-verification task, participants' response times were longer when the shape or orientation implied by the sentence (e.g., *He hammered the nail into the floor*) mismatched (a horizontal nail) than when it matched (a vertical nail) the picture of a nail (Stanfield & Zwaan, 2001; Zwaan et al., 2002). More recent findings have shown that the orientation of visually-presented objects can modulate reading times for sentences that implied the same (vs. a different) object orientation (Wassenburg & Zwaan, 2010). Other studies have investigated even subtler relationships between linguistic and non-linguistic information. For instance, Kaschak et al., (2005) reported that participants were slower in a sentence sensibility judgment task when motion described by a sentence was in the same (vs. the opposite) direction as simultaneously presented visual motion. In another study, Meteyard et al., (2008) found that low-level visual motion modulated lexical-decision times. Decision times were slower when motion words were incongruous (vs. congruous) with visual motion.

1.2. Visuo-spatial representations and abstract concepts: spatial distance and semantic similarity

The studies discussed above examined the processing of *concrete* words or sentences that were either explicitly or implicitly linked to aspects of the visual context. In these cases it is

arguably not surprising that visual context influences language comprehension rapidly and incrementally. What psycholinguistic research has not yet examined in detail is whether visual context effects are even more pervasive and could extend to *abstract* language comprehension.

Unlike concrete concepts, abstract concepts are not explicitly related to perceptual experience. In fact, some theories argue for a fundamental difference between concrete and abstract representations. The Dual Coding Theory (Paivio, 1986, 2013) proposes that concrete language is represented both at the linguistic level (through associations with other words) and at the perceptual level (through associations created during direct interaction with objects). By contrast, abstract language is represented only at the linguistic level, via associations with other words (see also Crutch & Warrington, 2005). Other theories, by contrast, would assume that abstract concepts are represented at the perceptual level, too, but in a more implicit manner compared to concrete concepts. Conceptual Metaphor Theory (Lakoff & Johnson, 1980, 1999), for instance, argues that abstract concepts such as *similarity* are structured and understood through metaphorical mapping from perceptual and motor experience (e.g., of spatial *closeness*), see (1) for examples:

(1)   a. Your ideas are *close* to mine.

b. My aims in this company are *far* from yours.

c. I can't tell the two theories *apart*.

What the examples in (1) reveal is that speakers use concrete spatial concepts (e.g., *close, apart, far*) when talking about more abstract ideas (e.g., *similarity*; see Lakoff, Espenson & Schwartz, 1991 for a compilation of similar expressions). Lakoff and Johnson (1980) interpreted these expressions as metaphorical, reflecting a relation between concrete (source) and abstract (target) domains. Consequently, concepts lacking direct experiential correlates (e.g., similarity)

are assumed to be metaphorically mapped onto more concrete representations (e.g., closeness)

that can be directly experienced. This hypothesis can generate predictions about the potential

role of visual-context representations in abstract language comprehension: When the concept of

semantic similarity is activated, the representation of closeness should also be active; and when

the concept of semantic dissimilarity is active, one might expect the representation of spatial

distance to be active, too (e.g., Gallese & Lakoff, 2005)[2].

Casasanto (2008) tested this hypothesis by asking participants to rate the similarity

between abstract nouns (Experiment 1) and unknown faces (Experiment 2), all of which were

presented either far apart or close to each other on a computer screen. When abstract words were

presented close to each other (vs. far apart), they were rated as more similar. Ratings for faces

were also modulated by spatial distance but showed the opposite pattern: Faces were rated as

more dissimilar when presented close together (vs. far apart). In a related study, Boot & Pecher

(2010) asked participants to perform speeded judgements on whether two squares were similarly

or differently colored. Response times were shorter when colored squares were similar and close

to each other (vs. far apart), and when differently-colored squares were far apart (vs. close to

each other). Together, Boot & Pecher (2010) and Casasanto's (2008) findings suggest that

representations of spatial distance are mapped onto the more abstract concept of similarity and

that this mapping modulates offline behavioral measures.

By contrast, evidence for the role of perceptual representations in abstract language

comprehension is mixed. A reaction time study (Richardson, Spivey, Barsalou, & McRae, 2003)

showed that the orientation (vertical vs. horizontal) implied by both concrete (e.g., *to sink*) and

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[2] Note that the present study is not aimed at testing the assumptions of Conceptual Metaphor Theory (i.e., how relations between spatial distance and semantic similarity emerge). Instead, we informed our hypothesis about potential links between visual information and abstract language from Conceptual Metaphor Theory.

abstract (e.g., *to hope*) sentential verbs modulated response latencies in an object discrimination task (whether a presented object was a square or a circle, Experiment 1). When an abstract verb implied a vertical orientation (e.g., *to hope*), response times were faster for horizontally than vertically aligned objects; when the verb implied a horizontal orientation (e.g., *argued with*), response times were faster for objects presented on the vertical (vs. horizontal) axis. Subsequent research with the same task, however, has replicated these results for concrete verbs only (Bergen, Lindsay, Matlock, & Narayanan, 2007). It is thus unclear whether perceptual information interacts with comprehension when language is abstract and when there are no referential or lexical-semantic links.

1.3. The present study

The present paper contributes to this burgeoning area of research by investigating (a) whether, and if so, to which extent, spatial distance between objects can modulate real-time semantic interpretation of abstract sentences; and (b) whether non-linguistic visual information can modulate language comprehension even in the absence of referential or lexical-semantic links. Participants inspected a visual context showing two objects (playing cards) moving close together (or farther apart) and subsequently read an unrelated sentence about two abstract nouns described as either semantically similar (e.g., 'war and battle are similar') or dissimilar ('war and peace are dissimilar'). We examined whether card distance could prime[3] the comprehension of semantic similarity and dissimilarity. By recording people's eye movements during sentence reading, we were able to observe the time course of this potential priming process.

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[3] 'Priming' is often used to refer to the advantage of processing a word (the target), after a previously- or concurrently-processed associated word (the 'prime', e.g., Anderson & Pirolli, 1984; Collins & Loftus, 1975; Meyer & Schvaneveldt, 1971). We use the term priming in a wider sense including clauses, sentences and pictures (cf. Coppens, Gootjes, & Zwaan, 2012; Connell & Lynott, 2012).

Current accounts of visually situated language comprehension (e.g., Altmann & Kamide, 2009; Knoeferle & Crocker, 2006, 2007) predict rapid visual context effects but are underspecified with regard to their representational assumptions. Thus, they are compatible with, but do not predict, rapid integration of perceptual and conceptual representations, such as spatial distance, and semantic similarity. Conceptual Metaphor Theory (Lakoff & Johnson, 1999), by contrast, motivates the link between spatial distance representations and semantic similarity but makes no predictions about the time course of any such effects during real-time sentence comprehension. Integrating mappings such as from spatial distance to semantic similarity into accounts of visually situated comprehension (e.g., the Coordinated Interplay Account (Knoeferle & Crocker, 2006, 2007) would allow us to make predictions about the effects of visual-context representations on the semantic interpretation of abstract concepts and the time course of such potential effects.

We predict that if the visual-context representation of spatial distance is pre-activated (via presentation of objects far apart or close together), it should prime the processing of ensuing abstract linguistic representation of semantic similarity. Specifically, we should see rapid effects of distance on the processing of semantic similarity during comprehension. These effects should appear closely time-locked to regions of the sentence in which semantic similarity becomes available. This prediction is motivated by the close temporal coordination between visual perceptual processes and the comprehension of (concrete) language that has informed accounts of visually situated language comprehension (see Knoeferle & Crocker, 2006, 2007).

There are at least two possibilities for how precisely spatial distance could prime the processing of semantic similarity. One possibility is that a visual-context representation of distance activates the concept of closeness, and such activation spreads to the associated abstract

concept of similarity (cf. Mahon & Caramazza, 2008). This should result in a local processing advantage at the sentence region which is lexically-associated with "close" or "far". Such local effects could be explained by a simple priming account. Alternatively, effects of spatial distance could appear in multiple regions of the sentence, including regions where semantic similarity is not explicitly mentioned but instead implied by conjoined words. Such effects would seem to implicate compositional processes and could not be straightforwardly explained by simple lexical-semantic priming (see Knoeferle et al., 2011, for a similar argument). Whether priming or compositional in nature, to the extent that effects of spatial distance on semantic similarity interpretation are rapid and incremental, situated language processing accounts will want to accommodate them.

In three eye-tracking experiments participants inspected a visual context (two playing cards depicted as moving apart from one another vs. close together) and subsequently read a sentence about abstract ideas that were either similar (e.g., *Battle and war are surely similar…*) or dissimilar (e.g., *Peace and war are certainly different…*). We varied between the experiments to which extent the visual context and the sentence were related; in this way we assessed visual context effects both when there was and when there wasn't an overt relation between the visual context and language. In Experiment 1, cards on critical trials presented two abstract nouns that re-appeared in the ensuing sentence. In Experiment 2, cards on critical trials were blank, but participants learnt the pairing of the abstract nouns in blocks, prior to reading the sentences. In Experiment 3, only blank cards were shown, thus eliminating any relation other than temporal contiguity between the visual context and the subsequent sentence.

2. Experiment 1

Recent evidence from a similarity-judgment study shows that two randomly paired written abstract words presented far apart were judged as less similar semantically compared to when the same words were presented close together (Casasanto, 2008, Experiment 1). In our first experiment we asked whether the effect of spatial distance extends to real-time comprehension during sentence reading. Participants inspected a visual context presenting two cards moving either close together or far apart. The cards had either two semantically similar or dissimilar abstract nouns written on them. Immediately after the card context, participants read a sentence containing the two nouns displayed on the cards and judged sentence veracity based on their world knowledge. If spatial distance effects generalize from similarity judgments to sentence comprehension, we should observe shorter reading times for sentences expressing dissimilarity and similarity between the two abstract nouns when the preceding words-on-cards were far apart and close to each other, respectively. Moreover, if spatial distance affects semantic interpretation incrementally, these effects should emerge at the point in the sentence where the relation between the two words is made explicit (either similar or dissimilar), namely the adjective region. Potentially, spatial distance effects could emerge even earlier, since at the *and*-coordination of the first two sentential nouns either semantic similarity or dissimilarity was already implied. Spatial distance effects at the conjoined nouns would suggest simple priming is not sufficient to accommodate the results. Finally, observing these effects in early reading time measures such as first-pass time or regression path duration, would suggest they are rapid; alternatively, spatial distance effects could appear in later measures, such as total times or later (post-adjective) in the sentence.

2.1. Method

2.1.1. Participants

Thirty-two native speakers of German (mean age: 23.6; range: 19-33 years old) with normal or corrected-to-normal vision from the Bielefeld University community received each 6 Euros for participation. None of them had been exposed to a second language before age 6. All participants gave informed consent.

2.1.2. Materials and Design

The visual context for experimental trials showed the images of two playing cards, each sized 155 x 265 pixels with a blue playing-card design on one side, and an abstract noun (e.g., *peace, war*) in black font (12 pts.) on its grey front side (see Figure 1). For experimental trials, we manipulated whether the cards (and thus the words on them) were close together (the two cards moved from their initial middle position close to each other) or far apart (the two cards moved from their initial position far apart from each other).
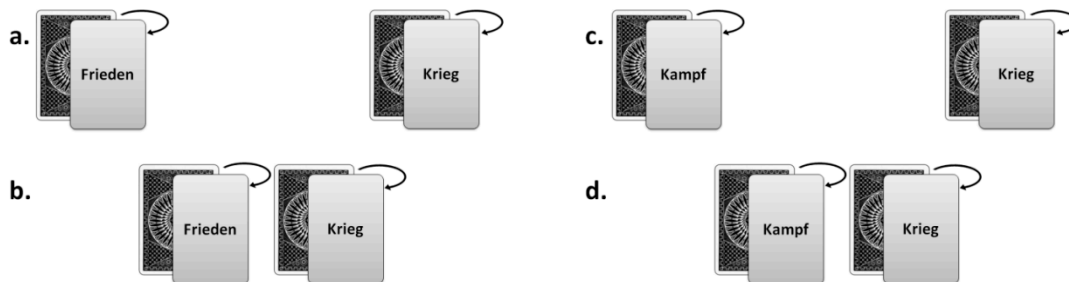
Figure 1. Example of visual contexts for the sentences in Table 1. Cards appeared on the screen showing their backside and turned, as indicated by the arrow, to present the two first sentential nouns in Experiment 1.

To inform construction of the sentences for the eye-tracking experiment, a different group of participants (n=16), rated pairs of abstract nouns (n=240) on a scale from 1 to 7 for their semantic similarity. Sixty pairs were synonymous and 120 antonymous, plus 30 related and 30 unrelated pairs as fillers. From these we selected the 48 noun pairs with the highest inter-rater

consensus[4] and constructed coordinated noun phrase sentences that either expressed dissimilarity

(e.g., '*Peace and war are certainly different, suggested the anthropologist*') or similarity (e.g.,

'*Battle and war are surely similar, suggested the anthropologist'*). Words that differed between

the sentences within an item (the first noun phrase, the adverb and the adjective) were matched

for number of characters and frequency[5].

Together the visual context (Close or Far) and sentence levels (Similar or Dissimilar)

resulted in four experimental conditions: Cards close to each followed by a sentence that

expressed similarity (Close-Similar); cards close to each other followed by a sentence that

expressed dissimilarity (Close-Dissimilar); cards far apart followed by a sentence that expressed

similarity (Far-Similar); and cards far apart followed by a sentence that expressed dissimilarity

(Far-Dissimilar, see Table 1).

Table 1: Example item sentences and the four conditions

Image	Sentence	Condition
Fig.1a	$Frieden_{NP1}$ $und_{coord.}$ $Krieg_{NP2}$ $sind_{VP1}$ $bestimmt_{ADV}$ $verschieden_{ADJ}$, das $verriet_{VP2}$ der $Anthropologe_{NP3}$.	Far-Dissimilar
Fig.1b	$Frieden_{NP1}$ $und_{coord.}$ $Krieg_{NP2}$ $sind_{VP1}$ $bestimmt_{ADV}$ $verschieden_{ADJ}$, das $verriet_{VP2}$ der $Anthropologe_{NP3}$.	Close-Dissimilar
Fig.1c	$Kampf_{NP1}$ $und_{coord.}$ $Krieg_{NP2}$ $sind_{VP1}$ $freilich_{ADV}$ $entsprechend_{ADJ}$, das $verriet_{VP2}$ der $Anthropologe_{NP3}$.	Far-Similar
Fig.1d	$Kampf_{NP1}$ $und_{coord.}$ $Krieg_{NP2}$ $sind_{VP1}$ $freilich_{ADV}$ $entsprechend_{ADJ}$, das $verriet_{VP2}$ der $Anthropologe_{NP3}$.	Close-Similar

Translation. Dissimilar sentence: 'Peace and war are certainly different, suggested the anthropologist';
Similar sentence: 'Battle and war are surely similar, suggested the anthropologist'.

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[4] Item 48 in all three experiments and item 47 in Experiments 1 and 3 were removed from the analysis due to an error in the order of word presentation (see Appendix A).
[5] Two paired sample *t*-test revealed no significant differences between the frequencies of the two groups of words or their length (both *t*-values (48) < 2, *p*-values > .05).

We used a Latin square design to assign items and experimental conditions to each

participant: Four lists were created, each of which contained the same number of trials per

condition and every item in only one condition. In addition each list contained 96 filler trials

(144 trials in total); 24 of the fillers displayed nouns on their front side and 72 had blank fronts.

The visual context was similar to the experimental trials varying either in the final position of the

two playing cards (e.g., top corners vs. bottom corners) or the color of them (e.g., red cards).

Trial presentation was pseudo-randomized such that all experimental sentences were either

preceded by one, two or three fillers, and never by another experimental item.

2.1.3. Procedure

Participants' eye movements were recorded using an Eyelink 1000 desktop head-

stabilized tracker (SR Research). At the beginning of the session, a 9-point calibration procedure

was carried out, and during the experiment additional recalibration was performed when

necessary. After the calibration, participants were presented 14 practice trials. Following the

practice trials the experiment began. Each trial was initiated by the experimenter, once

participants fixated a black dot in the middle of the screen. Figure 2 depicts the temporal order

of an experimental trial.
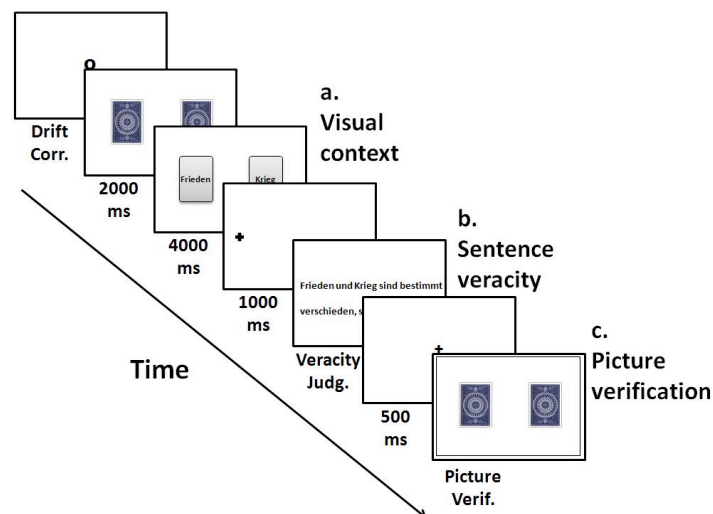
Figure 2. Schematic representation of an experimental trial for Experiment 1.

Every trial consisted of three main steps: In step 1 (Figure 2a), two playing cards (with their backside displayed) appeared at the bottom of the display and moved upwards to the middle of the screen. For experimental trials, cards then moved along the horizontal axis such that their final position was either far apart or close together (see Figure 1). After reaching their final position, the cards turned and showed each an abstract written noun for 4000 ms for all experimental trials and a third of the filler trials. For the remaining 72 fillers the cards turned and showed a blank front for 500 ms. Participants were instructed to carefully look at the cards and remember them. In step 2 (Fig. 2b), a black dot appeared for 1000 ms at the position where a subsequent sentence started. Participants were asked to focus on the black dot, carefully read the sentence and then judge sentence veracity based on their world knowledge by pressing a *yes* or a *no* button (Cedrus Response Pad 8-Buttons, Large). In the third and final step, participants inspected a static picture of two playing cards (Fig. 2c), and verified whether the two playing cards matched or mismatched the final position of the two playing cards they saw before reading the sentence. Participants pressed a *yes*-button when cards matched and a *no*-button when cards mismatched.

2.2. Data Analysis

Before the inferential analyses, contiguous fixations below 80 ms duration were merged. Isolated fixations < 80 ms that could not be merged with other fixations or fixations >1200 ms were excluded (see, e.g., Sturt, Keller, & Dubey, 2010). Furthermore, we removed trials with an incorrect response from the analysis. Critical sentences had eight different areas of interest as in (2). The main region of analysis was the adjective (ADJ) region in which the relation between the two abstract nouns was explicitly mentioned. We further examined the second noun phrase

(NP2) for possible earlier effects, and the second verb phrase (VP2) and the third noun phrase

(NP3), to see whether predicted effects could extend to later sentence regions.

(2)   *Frieden*$_{NP1}$ | *und*$_{coord.}$ | *Krieg*$_{NP2}$ | *sind*$_{VP1}$ | *bestimmt*$_{ADV}$ | *verschieden*$_{ADJ}$, |

       das verriet$_{VP2}$ | *der Anthropologe*$_{NP3}$.

       'Peace$_{NP1}$ | *and*$_{coord.}$ | *war*$_{NP2}$ | *are*$_{VP1}$ | *certainly*$_{ADV}$ | *different*$_{ADJ}$, |

       suggested$_{VP2}$ | *the anthropologist*$_{NP3}$'

Using the Data Viewer software (SR Research) we computed first-pass time, regression

path duration and total reading time. First-pass time is the sum of all fixations in an analysis

region prior to moving to another region. Regression path duration is the time from first entering

a region until moving to the right of that region; unlike first-pass time it includes reading time

following regressions out of the region (see, e.g., Konieczny, Hemforth, Scheepers, & Strube,

1997; Liversedge, Paterson, & Pickering, 1998; Rayner, 1998; Traxler, Pickering, & Clifton,

1998). Finally, total reading time is the duration of all fixations in a given region (Rayner &

Liversedge 2004; Rayner, 1998).

Kolmogoroff-Smirnov normality test confirmed that the data was positively skewed and

significantly diverged from the normal distribution for all regions and conditions. Thus, the raw

data were log-transformed prior to inferential analysis to improve normality of the distribution

(e.g., Tabachnik & Fidell, 2007, 246f.). Extreme data points for each interest region in each

condition were further removed if their deletion improved normality (2.5% of the overall data

and no more than 5% of the cases per condition). Removal of extreme cases and log-

transformation improved skewness and kurtosis, leading to non-reliable Kolmogorov-Smirnov

statistics (KS *p*s > .05), with the exception of the NP2 region.

A linear mixed-effect regression analysis (lme4 R) was conducted on log-transformed reading times data. Mixed models are useful in analyzing psycholinguistic data since these models allow simultaneous inclusion of crossed random factors for participants and items as an alternative to quasi-F and separate by-participants by-items analysis (F_1, F_2 analyses). They can also model participant and item variation around the fixed effects by including random slopes for participants and items. Furthermore, mixed models are robust against missing values and do not require homoscedasticity and sphericity assumptions to be met (Baayen, Davidson, & Bates 2008, Barr 2008, Quené & van den Bergh, 2004, 2008). The analysis produces estimates, standard errors and t-values for all main and interaction fixed effects. To evaluate significance we used the criteria of an absolute value of $t > 2$ (Baayen, 2008).

The two factors and their interactions (i.e., spatial distance and semantic similarity) constituted the fixed effects in our mixed model. We centered the factors using a *scale* function[6] in R to minimize collinearity between them. This function centers the data on a mean of 0 and a range of 2. Both participants and items were included as crossed random intercepts and we always included all random slopes justifiable by our experimental design[7]. The omission of random slopes in linear mixed-effects regressions has been discussed as anti-conservative (Sturt et al., 2010), and is thought to increase the risk of Type I errors (Barr, Levy, Scheepers & Tily, 2013). The R-code for the full model was the following: lmer (dv ~ iv1*iv2 + (1 + iv1*iv2 | participant) + (1 + iv1*iv2 | item), data). The "dv" in the R-code represents the dependent variable (for instance, first-pass time), and "iv1" and "iv2" represent the two independent variables (i.e., spatial distance and semantic similarity). This model includes fixed effects for the

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[6] (data$factor=scale(as.numeric(data$factor)))

[7] For measures in which we found interaction effects with the linear mixed-effect regression we also performed 2 x 2 repeated measures ANOVAs by participants and items. These support the conclusions from the linear mixed-effects regression analyses (see Table B2 in Appendix B).

two factors, the interaction between them, participants and items as random intercepts, and both main and interaction effects as random slopes for both random intercepts.

Whenever the full model did not converge, we followed the recommendations by Barr and colleagues (2013). We began by increasing the number of iterations in the estimation procedure, which resulted in convergence for most of our models. When this strategy was not effective, we simplified the model's random effects structure (see Barr et al. 2013) by removing random effects correlations for participants and items[8]. For those regions and measures in which we observed a reliable interaction of the factors we also report pairwise comparisons. These consisted of a full linear mixed-effect regression on the influence of spatial distance for either a) sentences that expressed similarity, or b) sentences that expressed dissimilarity between abstract nouns. These analyses permit detailed insight into spatial distance effects within a sentence condition; nevertheless they suffer from a loss of power due to splitting the data. Moreover, our within-subject within-item design is aimed to reveal interaction effects, if they exist.

2.3. Results

Table 2 shows mean reading times in milliseconds per condition, for all measures and regions analyzed. Results of the linear mixed-effect regression analyses are presented in Table 3. Figure 3 illustrates the interaction effect between spatial distance and semantic similarity. At the NP2 region no reliable effects were observed. At the critical adjective region (ADJ), a pervasive similarity main effect emerged in all measures: reading times were shorter for sentences expressing similarity compared to those expressing dissimilarity (all ts > 2.63). As predicted, we found a reliable interaction between spatial distance and semantic similarity ($t = -2.08$) in first-

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[8] This was true only for one contrast (first-pass reading times for the VP2 in sentences expressing similarity), and the R code used was: lmer (first-pass ~ distance*similarity + (1 | participant) + (0+distance*similarity | participant) + (1 | item) + (0+ distance*similarity | item), data).

pass reading time at the ADJ region. Reading times were shorter when similarity-conveying sentences were preceded by cards-with-words presented close to each other (vs. far apart) and reading times for sentences that conveyed dissimilarity were shorter when preceded by cards-with-words presented far apart (vs. close to each other; all other ts < 2). Reliable interaction effects emerged also at the VP2 and NP3 regions in first-pass reading times (t = -2.09 and t = -2.39, respectively) and in total reading times at NP3 (t = -2.58), all of them with the same gaze pattern as for the ADJ region.

Table 2. Mean reading times in milliseconds and standard errors of the mean (by condition, region and measure) in Experiment 1.

Region	Condition	*First-pass*		*Regression path*		*Total time*	
		Mean	*SE*	**Mean**	*SE*	**Mean**	*SE*
NP2	Far-Dissimilar	174.23	3.5	220.48	8.3	436.54	23.2
	Close-Dissimilar	187.59	5.4	236.75	10.1	444.63	23.2
	Far-Similar	180.49	4.3	222.54	9.0	442.58	24.8
	Close-Similar	181.29	4.7	233.50	9.6	402.87	19.4
ADJ	Far-Dissimilar	328.32	7.7	408.58	12.5	416.30	10.9
	Close-Dissimilar	337.73	9.1	420.35	13.5	429.66	13.4
	Far-Similar	311.79	8.0	377.34	12.5	354.49	8.7
	Close-Similar	293.71	7.1	368.69	12.2	345.08	9.4
VP2	Far-Dissimilar	211.14	4.8	296.34	13.8	238.49	6.6
	Close-Dissimilar	239.54	7.1	307.95	12.7	289.99	14.0
	Far-Similar	218.60	5.7	312.94	14.1	253.19	8.8
	Close-Similar	212.28	5.6	340.24	16.8	250.95	8.0
NP3	Far-Dissimilar	333.13	14.1	973.70	59.7	404.82	17.3
	Close-Dissimilar	353.14	12.1	1006.58	61.3	418.43	15.3
	Far-Similar	340.58	16.2	964.22	57.9	394.51	18.9
	Close-Similar	318.26	11.1	849.97	45.4	367.87	13.4

Finally, we explored the observed pattern of interaction using pairwise comparisons. For first-pass reading times at the ADJ region, pairwise comparison showed a reliable effect of spatial distance for sentences expressing similarity only (t = 2.05; sentences expressing

dissimilarity: $t < 1$). By contrast, for the VP2 we found a marginally significant effect of

distance for sentences that expressed dissimilarity only ($t = -1.97$). Similarly, at the NP3 reliable

spatial distance effects were found only for sentences that expressed dissimilarity (first pass

reading times: $t = -2.77$ and total reading times: $t = -2.84$; for sentences expressing similarity: $t <$

1 in both measures).

Table 3. Main and interaction effects (by region and measure) in the linear mixed-effect

regression on log-transformed reading times in Experiment 1.

Region	Fixed Effects	First-pass				Regression path				Total times			
		Estimate	SE	t		Estimate	SE	t		Estimate	SE	t	
NP2	(Intercept)	5.130	0.024	211.76		5.274	0.037	143.06		5.739	0.068	84.18	
	distance	-0.011	0.011	-1.00		-0.022	0.017	-1.30		-0.011	0.025	-0.45	
	similarity	0.002	0.011	0.22		0.006	0.015	0.38		-0.002	0.032	-0.07	
	interaction	-0.010	0.012	-0.79		0.004	0.018	0.21		-0.015	0.020	-0.75	
ADJ	(Intercept)	5.680	0.032	178.34		5.856	0.042	137.01		5.856	0.036	165.30	
	distance	0.009	0.013	0.74		0.000	0.013	0.01		0.009	0.012	0.74	
	similarity	0.047	0.018	2.63	*	0.058	0.018	3.38	*	0.085	0.019	4.46	*
	interaction	-0.023	0.011	-2.08	*	-0.017	0.014	-1.18		-0.015	0.013	-1.18	
VP2	(Intercept)	5.309	0.030	177.46		5.549	0.039	142.37		5.423	0.037	147.98	
	distance	-0.014	0.014	-0.96		-0.026	0.021	-1.21		-0.029	0.015	-1.95	#
	similarity	0.021	0.013	1.78	#	-0.017	0.018	-0.93		0.017	0.015	1.09	
	interaction	-0.027	0.013	-2.09	*	0.001	0.022	0.04		-0.024	0.016	-1.56	
NP3	(Intercept)	5.623	0.048	116.39		6.457	0.077	83.42		5.785	0.053	108.09	
	distance	-0.038	0.019	-1.96	#	-0.012	0.032	-0.38		-0.028	0.017	-1.62	
	similarity	0.008	0.017	0.47		0.012	0.028	0.43		0.020	0.021	0.98	
	interaction	-0.045	0.019	-2.39	*	-0.048	0.030	-1.61	#	-0.047	0.018	-2.58	*

Note: #$p <.1$. *$p <.05$.

2.4. Discussion

In our first experiment, we observed spatial distance effects at the ADJ and subsequent

regions in first-pass reading times, suggesting they occur rapidly and incrementally. The effects

at the VP2 and NP3 regions echoed the reading-time pattern at the ADJ, suggesting that spatial

information can have an extended effect during sentence interpretation. The absence of reliable

effects of spatial distance before the adjective (at NP2) suggests that spatial information can

modulate semantic similarity in a sentence context as soon as it is explicitly mentioned (at the

ADJ), but perhaps not if it is implied by *and*-coordinated noun phrases (e.g., *'peace and*

war...')[9]. Results from Experiment 1 are to the best of our knowledge the first evidence that

visually-depicted spatial distance can affect incremental sentence interpretation (of similarity

between two abstract nouns).
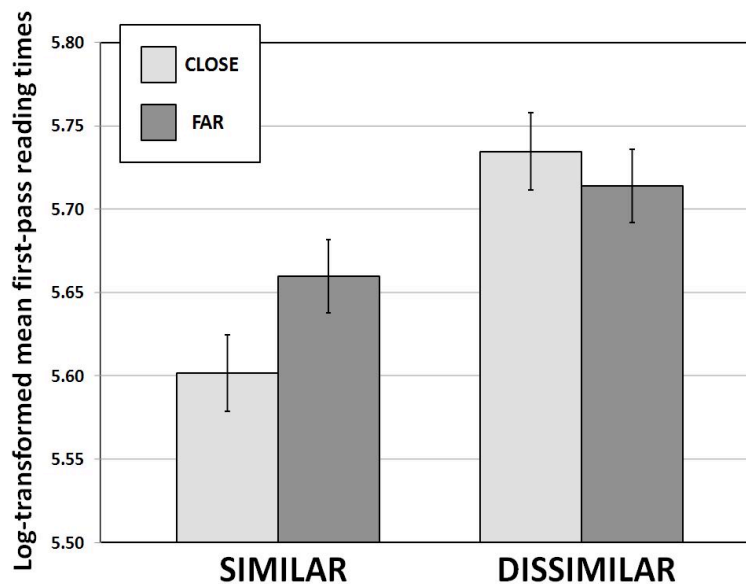
Figure 3: Log-transformed mean first-pass time (with error bars plotting the standard

error of the mean) for the ADJ region as a function of sentence type and spatial distance between

cards-with-words in Experiment 1.

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[9] It is possible that the pre-sentence presentation of written nouns (which then re-appeared as NP1 and NP2 in the sentence) induced shallow semantic processing of the NP2. In fact, positive skew values for first-pass reading times at NP2 indicate short inspection times (skew after log-transform = .678, *SE*=.077). Repetition of words can speed up both word recognition and categorization (see Jacoby, 1983). This could be especially true for the NP2, since NP1 could have served as a cue of the previously seen word-pair. Such a reading strategy could have obscured potential spatial distance effects at the NP2 region on the assumption that deep semantic processing is pre-requisite for spatial distance effects on semantic interpretation.

Rapid and incremental spatial distance effects could occur when card distance is integrated with noun phrase similarity incrementally, during sentence comprehension. Indeed, existing evidence has shown that semantic information from adjectives can be rapidly integrated with simultaneously presented non-linguistic visual information (e.g., Sedivy et al., 1999). However, it is also possible that the words displayed on the cards in Experiment 1 enabled pre-sentence integration of word meaning and card distance, since the two abstract nouns on the cards implied either semantic similarity or dissimilarity; perhaps this pre-sentence integration was responsible for the rapid spatial distance effects observed during sentence comprehension. Experiment 2 addressed this question.

3. Experiment 2

In our second experiment, we detached the nouns from the spatial information conveyed by the visual context. If the rapid and incremental effects of spatial distance need pre-sentence integration of spatial distance with word meaning, then we should observe no, or delayed, spatial distance effects when the nouns are presented temporally separated from the card context. Alternatively, if pre-sentence integration is not essential, then we should see rapid and incremental spatial distance effects emerge even when the words are presented temporally separated from the cards and the sentence trials.

To disentangle these two possibilities, we divided the experiment into six blocks of trials. Before each block, participants read and learnt a list of written noun pairs (among them all critical pairs of nouns of that block and an equal number of filler word pairs). In contrast with Experiment 1, the cards preceding each sentence remained blank. Consequently, participants saw the same noun pairs as in Experiment 1 but temporally detached from the cards and the sentences. Therefore, participants could neither predict the semantic relationships between

words of a given sentence nor integrate the card distance with these semantic relations prior to sentence reading.

3.1. Method

3.1.1. Participants

Thirty-two further native speaker of German with normal or corrected-to-normal vision (mean age: 23.19; range 19-29) participated in the experiment for a monetary compensation of 6 Euro. None of them had been exposed to a second language before age 6. All participants gave informed consent.

3.1.2. Materials and Design

The sentences and the experimental design were identical to Experiment 1 with the only difference that cards on all of the critical trials remained blank. The experiment-wide ratio of cards-with-words to blank cards was kept constant by including written words on the cards of 72 filler trials. Moreover, while in Experiment 1 blank cards were presented for 500 ms and cards-with-words for 4000 ms after they turned around, in Experiment 2 cards both blank fronts and written words were presented for 3000 ms to eliminate presentation-related differences between these trials.

3.1.3. Procedure and analysis

Both analysis and procedure were identical to Experiment 1 with the following exception: Experiment 2 was divided in six blocks of 24 trials each. Participants learnt a list of 16 word pairs (8 critical and 8 filler pairs) before each block of trials. These pairs appeared in 16 of the 24 sentences in a block. Participants were given the list of word-pairs to study. After they declared knowing the word pairs, a memory test ensured a minimum of 75% of accuracy for each list. The same procedure was repeated on each block.

3.3. Results

Accuracy on the test lists was high for all participants (mean = 96.8%, range = 95-100%) suggesting they were able to memorize the noun pairs. Table 4 shows mean reading times in milliseconds per condition, for all measures and regions analyzed. Table 5 presents the results from the linear mixed-effect regression analyses.

Table 4: Mean reading times in milliseconds and standard errors of the mean (by condition, region and measure) in Experiment 2.

Region	Condition	First-pass		Regression path		Total time	
		Mean	SE	Mean	SE	Mean	SE
NP2	Far-Dissimilar	229.46	5.18	298.05	11.34	465.67	19.51
	Close-Dissimilar	227.09	5.09	261.97	7.08	453.04	20.22
	Far-Similar	224.87	5.06	242.40	5.91	498.36	21.51
	Close-Similar	225.07	5.08	249.76	6.54	423.43	15.52
ADJ	Far-Dissimilar	330.47	7.48	402.16	10.98	389.54	10.02
	Close-Dissimilar	334.47	8.26	437.23	13.26	433.52	11.79
	Far-Similar	350.36	9.59	397.96	11.66	405.27	12.17
	Close-Similar	330.15	7.96	379.67	10.65	389.19	10.90
VP2	Far-Dissimilar	227.96	6.23	329.58	14.77	292.55	11.43
	Close-Dissimilar	227.15	5.53	300.67	11.15	283.03	9.56
	Far-Similar	240.62	6.73	289.34	9.15	311.67	12.70
	Close-Similar	227.65	5.56	297.63	11.08	318.00	13.75
NP3	Far-Dissimilar	354.40	12.29	951.21	48.98	426.59	16.44
	Close-Dissimilar	357.01	12.67	1028.25	57.45	432.37	16.24
	Far-Similar	380.99	14.66	1170.14	57.51	464.08	16.83
	Close-Similar	379.55	14.75	1152.59	64.42	466.12	17.79

The analyses confirmed a main effect of similarity in regression path duration at the NP2 region (all other ts < 2). At the ADJ region a main effect of similarity and a marginally significant interaction effect between spatial distance and semantic similarity were found in regression path duration ($t = -1.89$). Further, a reliable interaction effect was seen in total

reading times ($t = -2.43$). In these two measures, reading times were shorter for sentences

expressing similarity when the sentence were preceded by cards close to each other compared to

far apart; by contrast, the ADJ region of sentences that expressed dissimilarity showed shorter

reading times when the preceding cards were far apart compared to close together. For the NP3

region, the main effect of similarity was reliable in regression path duration and total reading

times (all other ts < 2).

Table 5: Main and interaction effect results (by region and measure) of the linear mixed-

effect regression for log-transformed reading times in Experiment 2.

Region	Fixed Effects	*First-pass*			*Regression path*			*Total times*		
		Estimate	*SE*	*t*	Estimate	*SE*	*t*	Estimate	*SE*	*t*
NP2	(Intercept)	5.353	0.032	**169.71**	5.462	0.042	**130.12**	5.904	0.064	**91.16**
	distance	0.003	0.014	**0.22**	0.007	0.015	**0.43**	0.025	0.016	**1.57**
	similarity	0.011	0.011	**0.96**	0.042	0.018	**2.39** *	-0.012	0.021	**-0.57**
	interaction	-0.001	0.010	**-0.12**	0.019	0.012	**1.49**	-0.026	0.017	**-1.54**
ADJ	(Intercept)	5.730	0.031	**184.08**	5.888	0.034	**173.67**	5.895	0.038	**155.86**
	distance	0.008	0.012	**0.68**	-0.009	0.012	**-0.73**	-0.017	0.012	**-1.39**
	similarity	-0.004	0.016	**-0.25**	0.034	0.016	**2.11** *	0.024	0.017	**1.40**
	interaction	-0.015	0.013	**-1.18**	-0.027	0.014	**-1.89** #	-0.034	0.014	**-2.43** *
VP2	(Intercept)	5.357	0.031	**170.54**	5.561	0.040	**140.78**	5.530	0.045	**121.80**
	distance	0.001	0.013	**0.09**	0.007	0.017	**0.44**	-0.009	0.016	**-0.51**
	similarity	-0.009	0.013	**-0.66**	0.018	0.018	**1.03**	-0.022	0.021	**-1.06**
	interaction	-0.010	0.012	**-0.79**	0.006	0.017	**0.33**	-0.000	0.017	**0.02**
NP3	(Intercept)	5.717	0.056	**102.36**	6.580	0.096	**68.56**	5.904	0.056	**104.54**
	distance	-0.002	0.018	**-0.1**	0.003	0.023	**0.14**	-0.003	0.016	**-0.20**
	similarity	-0.016	0.017	**-0.92**	-0.067	0.025	**-2.73** *	-0.036	0.017	**-2.18** *
	interaction	-0.002	0.016	**-0.13**	-0.027	0.022	**-1.26**	-0.001	0.016	**-0.04**

Note: #p <.1. *p <.05.

Pairwise comparisons for regression path duration and total reading time at the ADJ

region showed no reliable effect of spatial distance for sentences that expressed similarity (ts <

2) but a marginal and a reliable effect of spatial distance for sentences that expressed dissimilarity were observed, respectively (regression path duration, $t = -1.97$; total reading times $t = -2.83$).

3.4. Discussion

In our first experiment we observed that spatial distance modulated semantic interpretation, and it did so rapidly and incrementally. However, it was not clear whether these effects depended on spatial-semantic integration prior to sentence reading. We separated the semantic information provided by the words from spatial information in the visual context, and replicated spatial distance effects in Experiment 2. As in Experiment 1, spatial distance effects did not emerge at NP2 but only later, once semantic similarity was explicitly mentioned (the ADJ region). This results show that spatial distance can modulate the interpretation of semantic relations between abstract concepts when it is explicitly mentioned and even when spatial distance has to be integrated with semantic similarity on the fly.

While spatial distance effects emerged consistently at the ADJ region, they appeared in an earlier measure (first-pass reading times) in Experiment 1 compared to Experiment 2 (marginal in regression path duration, and significant in total reading times). The delay could have resulted from the immediate integration of card distance with the semantic relations during sentence processing. Alternatively (or in addition), the first noun phrase of the sentence may have cued retrieval of previously seen or learnt semantic relations. This retrieval process and the integration of studied word pairs with the sentence content and spatial distance information could have delayed the spatial distance effects.

4. Experiment 3

In our third experiment, the cards for all trials were blank in Experiment 3, and participants saw no word pairs before sentence reading. Thus, upon encountering the cards or even the first noun phrase in a critical sentence, participants did not have any information about the semantic relations expressed by the sentence. If retrieval processes delayed spatial distance effects in Experiment 2 but otherwise the integration of semantic relations and spatial distance during comprehension can occur rapidly, then we should observe effects of spatial distance in first-pass times in Experiment 3.

Moreover, Experiment 3 examined spatial distance effects on semantic interpretation in the absence of any links other than temporal contiguity (the cards appeared immediately before the sentence). Card distance was irrelevant to the sentence comprehension task in all three experiments, but in the first two experiments the visual context was somehow related to the sentence via words on the cards. Experiment 3 thus provides a strong test of whether spatial distance alone can modulate the incremental semantic interpretation of similarity relations.

4.1. Method

4.1.1. Participants

Another thirty-two native speakers of German with normal or corrected-to-normal vision (mean age: 24,37; range 20-31) participated in the experiment for a monetary compensation of 6 Euro. None of them had been exposed to a second language before age 6. All participants gave informed consent.

4.1.2. Material, design, procedure and data analysis

Critical sentence stimuli, design, procedure and analysis were the same as in Experiment 1. However, cards on all trials were blank in Experiment 3. As in Experiment 2, cards turned around after 3000 ms and presented the front side for another 3000 ms.

4.2. Results

Table 6 shows mean reading times in milliseconds per condition, for all measures and analyzed regions. Table 7 shows the results from the linear mixed-effect regression analyses. At the NP2 we found a marginally significant main effect of similarity in first-pass time ($t = $ -1.98) as well as a significant interaction of spatial distance and semantic similarity ($t = $ -2.15). First-pass time for sentences that expressed similarity were shorter when cards were close together (vs. far apart), while first-pass time for sentences that expressed dissimilarity were shorter when preceded by cards far apart (vs. close together). No other effects were observed for this region. At the ADJ region we observed a statistically significant similarity main effect in regression path duration (other ts < 2). Analysis of the VP2 showed a reliable interaction between spatial distance and semantic similarity ($t = $ -2.07; all other ts < 1). Finally, at the NP3 region we found reliable main effects for both spatial distance and semantic similarity (ts > 2) in regression path duration (other ts < 2).

Table 6: Mean reading times in milliseconds and standard errors of the mean (by condition, region and measure) in Experiment 3.

Region	Condition	First-pass		Regression path		Total time	
		Mean	*SE*	**Mean**	*SE*	**Mean**	*SE*
NP2	Far-Dissimilar	313.71	9.57	434.60	19.91	614.25	23.43
	Close-Dissimilar	354.92	11.78	411.96	14.49	614.59	22.63
	Far-Similar	300.14	8.42	415.25	19.59	608.56	27.23
	Close-Similar	290.28	8.63	382.56	19.37	635.67	29.73
ADJ	Far-Dissimilar	363.66	8.99	436.77	12.19	427.85	11.24
	Close-Dissimilar	350.02	9.72	428.57	13.02	442.61	14.23
	Far-Similar	334.79	9.08	389.74	11.66	409.38	11.91
	Close-Similar	343.45	9.96	405.83	13.65	432.26	14.87
VP2	Far-Dissimilar	229.47	5.86	297.56	10.44	269.98	8.42
	Close-Dissimilar	249.01	7.15	334.17	13.59	308.65	11.09
	Far-Similar	239.95	6.16	336.13	13.38	299.32	10.68
	Close-Similar	236.70	6.80	337.50	14.88	331.05	16.33

NP3	Far-Dissimilar	393.35	15.44	1095.71	61.03	475.64	19.26
	Close-Dissimilar	419.48	17.99	1131.12	57.81	497.81	19.62
	Far-Similar	402.99	15.75	1198.33	63.58	526.88	20.49
	Close-Similar	411.50	18.62	1283.04	70.90	514.92	20.56

Qualitatively, the gaze pattern underlying the interaction at NP2 and VP2 resembled that at the ADJ region in Experiments 1 and 2. Pairwise comparisons for first-pass time at NP2 revealed reliable effects of spatial distance for sentences that expressed dissimilarity ($t = -2.03$; other ts < 2).

Table 7: Main and interaction effects (by region and measure) of the linear mixed-effect regression for log-transformed reading times in Experiment 3.

Region	Fixed Effects	*First-pass*			*Regression path*			*Total times*		
		Estimate	*SE*	*t*	Estimate	*SE*	*t*	Estimate	*SE*	*t*
NP2	(Intercept)	5.629	0.050	**112.38**	5.820	0.056	**104.74**	6.195	0.068	**91.32**
	distance	-0.017	0.015	**-1.16**	0.012	0.018	**0.68**	-0.024	0.020	**-1.18**
	similarity	0.036	0.019	**1.94** #	0.023	0.022	**1.07**	-0.002	0.024	**-0.09**
	interaction	-0.029	0.013	**-2.15** *	-0.018	0.021	**-0.84**	0.000	0.017	**0.02**
ADJ	(Intercept)	5.752	0.038	**153.12**	5.917	0.037	**159.68**	5.935	0.045	**131.99**
	distance	0.011	0.012	**0.91**	0.005	0.013	**0.38**	-0.003	0.013	**-0.25**
	similarity	0.026	0.018	**1.43**	0.050	0.021	**2.38** *	0.024	0.017	**1.38**
	interaction	0.019	0.012	**1.56**	0.014	0.014	**0.99**	0.003	0.013	**0.24**
VP2	(Intercept)	5.381	0.034	**160.22**	5.624	0.041	**136.85**	5.546	0.046	**120.43**
	distance	-0.004	0.016	**-0.27**	-0.005	0.020	**-0.28**	-0.022	0.017	**-1.31**
	similarity	-0.001	0.012	**-0.07**	-0.020	0.017	**-1.21**	-0.017	0.017	**-1.00**
	interaction	-0.025	0.012	**-2.07** *	-0.031	0.020	**-1.51**	-0.026	0.018	**-1.46**
NP3	(Intercept)	5.776	0.056	**103.23**	6.691	0.084	**79.56**	5.975	0.069	**86.59**
	distance	-0.025	0.019	**-1.31**	-0.056	0.024	**-2.31** *	-0.026	0.017	**-1.50**
	similarity	0.007	0.019	**0.39**	-0.058	0.024	**-2.41** *	-0.030	0.019	**-1.57**
	interaction	-0.009	0.019	**-0.53**	0.001	0.025	**0.05**	-0.014	0.018	**-0.75**

Note: #p <.1. *p <.05.

4.3. Discussion

The analyses in Experiment 3 revealed a rapid (first-pass) and incremental (at the NP2 region) interaction of spatial distance and semantic similarity. These results show that even in the absence of any overt relation between a visual context and subsequent sentence content, non-linguistic spatial information can affect the semantic interpretation of conjoined abstract nouns.

We observed spatial distance effects at the NP2 region in Experiment 3 and therefore earlier in the sentence compared to the first two experiments. Potentially the absence of earlier interaction effects (at NP2) in the first two experiments resulted from the repetition of the words. Seeing the two abstract words before the sentence might have prompted participants to process the and-coordination more superficially during sentence reading, such that its meaning was not immediately integrated with spatial distance. On the other hand, the earlier effects in Experiment 3 (at NP2) than Experiment 2 (in regression path times at the ADJ region) suggest that the relative delay we observed in Experiment 2 was unlikely caused by immediate integration of semantic similarity and spatial distance and more likely resulted from the cued retrieval of previously-learnt semantic relations.

One issue remains: It is unclear why effects of spatial distance were absent at the ADJ region in Experiment 3, while they were present in Experiments 1 and 2. One possibility is that integration of spatial information and implicit semantic similarity at the NP2 drew attention to spatial distance in a way that changed the effects of spatial distance at the downstream ADJ region. Tentative evidence for the view that spatial distance and semantic similarity processing interacted in a different way at the ADJ region in Experiment 3 (compared to the first two experiments) comes from the different reading-time pattern at that region (first pass reading times for similarity-conveying sentences were *longer* when cards were close together than far

apart). Overall, our results are the first experimental data showing rapid and incremental effects of spatial distance on the semantic interpretation of abstract language.

5. General Discussion

Three eye-tracking reading experiments assessed whether spatial distance between objects could rapidly and incrementally facilitate the semantic interpretation of abstract sentences when distance information was not mediated by referential or lexical-semantic links. We manipulated the semantic content of written sentences (similarity vs. dissimilarity between two abstract nouns) and spatial distance in the visual context (playing cards moving closer together or farther apart). Spatial distance and semantic similarity were never referentially or lexico-semantically linked[10], and between experiments, we varied their relatedness. In our first experiment, cards showed two abstract nouns that re-appeared in the ensuing sentence on critical trials. In our second experiment, cards were blank on critical trials but participants learnt the pairing of abstract nouns in blocks, prior to reading the sentences, and on most filler trials cards showed words that re-appeared in the subsequent sentence. In our third experiment, cards in the visual context were always blank, thus eliminating any overt relation other than temporal contiguity between card distance and the (semantic similarity of the) sentential nouns.

In Experiment 1, we observed faster reading times when sentences about similarity were preceded by cards-with-words close to each other (vs. far apart), and when sentences that expressed dissimilarity were preceded by cards-with-words far apart (vs. close together). This reading time pattern was reliable at the ADJ, the VP2 and the NP3 regions in first-pass reading times. In Experiment 2, the same reading time pattern emerged at the ADJ, however, in later

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[10] It might be argued that the repetition of words (on the cards and in the sentence) counts as a 'referential' link. Note, however, that merely relating individual words on the cards to words in the sentence could not have caused the observed spatial distance effects. Rather, for these effects to emerge, participants must process the distance between two objects, the semantic similarity between two abstract nouns, and then integrate these two representations.

measures (total times). Together the first two experiments showed that when visual context was related to a subsequent sentence (through words on cards for critical items in Experiment 1; through words on cards for filler items in Experiment 2), then spatial distance facilitated the interpretation of semantic similarity between two abstract nouns.

In Experiment 3 we had removed any overt relation between the cards in the visual context and the subsequent sentence. Nevertheless, we replicated rapid and incremental spatial distance effects. When two blank cards were presented either close together or farther apart in the visual context, spatial information rapidly influenced incremental semantic interpretation of sentences about similarity or dissimilarity between two abstract nouns. First-pass times at NP2 and VP2 for sentences expressing semantic similarity were shorter when preceded by cards close to each other compared to far apart and they were longer for sentences expressing dissimilarity when cards were far apart compared to close to each other.

5.1. Visual-context representation and abstract sentence processing: beyond lexical priming

The results from these three experiments revealed that non-linguistic visual information can rapidly and incrementally modulate the semantic interpretation of abstract sentences and that this can happen even in the absence of referential or lexical-semantic links. One potential mechanism underlying this effect could be lexical priming. A recent study, for instance, showed rapid effects of *abstract* language on visual attention during spoken language comprehension. When participants heard an abstract word (e.g., '*smell*'), they inspected an object (e.g., a nose) associated with that word more often than non-associated objects (Duñabeitía, Avilés, Afonso, Scheepers, & Carreiras, 2009). Previous studies have demonstrated that *concrete* language can guide visual attention to unmentioned objects, for instance, through subtle associations between a color adjective and the color of an object (e.g., Dahan & Tanenhaus, 2005; Huettig & Altmann,

2011; Huettig & McQueen, 2007). These effects are triggered by specific lexical input; they seem insensitive to linguistic contextual appropriateness (see Huettig & Altmann, 2007); and they can be accommodated by a lexical-associative account. In this regard they are indeed different from our findings.

The new insight from our results is that a visual-context representation (i.e., of spatial distance between playing cards) selectively modulates semantic similarity between two abstract nouns during incremental semantic interpretation. To accommodate these results, lexical-semantic priming (e.g., spreading activation from a word to a concept) is not sufficient. Spreading-activation has been proposed to explain semantic priming in a single-word context (e.g., Anderson & Pirolli, 1984; Collins & Loftus, 1975; Hutchinson, 2003), and also in the context of real-time sentence comprehension (e.g., Carroll & Slowiaczek, 1986; Morris, 1994).

At first blush, the effect in our studies might seem to arise from simple priming of individual lexical items (e.g., when participants encounter the word 'similar', they process it faster if they had previously activated the concept of spatial proximity rather than distance). Critically, the time course of the reported effects in the context of our sentence stimuli permits us to exclude a lexical-semantic priming account. Results from Experiment 3 show that spatial distance effects appeared at the earliest possible point in time (i.e., in first-pass times at the NP2 region), where semantic similarity (or dissimilarity) was implied by the combination of the first two noun phrases. This effect cannot be explained through lexical-semantic priming alone, since similarity was not conveyed by just one word (e.g., '*battle*'). Instead, it arises from the interpretation of the *and*-coordination of two abstract synonyms ('*Battle and war*') or antonyms ('*Peace and war*'). The observed facilitation or priming therefore required compositional processing. In Experiment 1 similar effects occurred only in subsequent regions (ADJ, VP2, and

NP3). Word repetition might have discouraged deep semantic processing of the first two

sentential nouns in Experiment 1 (see Jacoby, 1983), such that semantic similarity and spatial

distance representations were not integrated at the NP2. Nevertheless, the effects extended from

the ADJ region to the next two sentence regions (VP2, NP3). Again these extended effects are

unlikely best accommodated by lexical semantic priming alone.

5.2. Implications for processing accounts of language in context

In sum, the results from these three experiments are the first evidence for rapid effects of

non-referential spatial information on the incremental comprehension of abstract language. One

interesting question concerns how we could accommodate these new results in existing accounts

of situated language processing. Such accounts predict a close temporal coordination between

when words in the utterance mediate relevant aspects of visual context and when visual context

affects language comprehension (e.g., Knoeferle & Crocker, 2006, 2007; Tanenhaus, Magnuson,

Dahan, & Chambers, 2000). In particular, the Coordinated Interplay Account (Knoeferle &

Crocker, 2007) assumes that the partial sentence interpretation can rapidly guide (visual)

attention to relevant scene information or representations thereof in working memory. Linguistic

and non-linguistic visual context representations are then co-indexed and in this process visual

context representations can influence on-going language comprehension. Co-indexing occurs

via reference between nouns and concrete objects, or verbs and concrete actions in the

Coordinated Interplay. With respect to abstract language and non-referential contexts, two

interesting issues arise: First, how does language guide attention to relevant visual-context

representations (of spatial distance)? And second, how are these representations of the visual

context co-indexed with the linguistic representations?

Consider the first of these two issues: In our experiments, participants were instructed to attentively inspect the visual context and keep it in memory. At the beginning of a sentence, their working memory presumably included representations of spatial distance, card colour, and position, amongst others. Next, participants encountered the sentence-initial noun phrase coordination. The interpretation of these noun phrases as semantically similar or dissimilar could direct their attention to the spatial-distance representations, and these would then be integrated with the unfolding interpretation (the representations of the noun phrases and of the adjectival term). This account (that interpretation of the noun phrases singles out pre-activated distance representations) fits well with the time course of spatial distance effects in Experiment 3. When the cards were entirely unrelated to the sentence (Experiment 3), the two noun phrases were processed in-depth and compositional semantic interpretation of these noun phrases singled out relevant visual context representations, eliciting spatial distance effects on semantic interpretation. By contrast, when participants either encountered the noun pairs immediately before the sentence (Experiment 1) or learnt them minutes before sentence reading (Experiment 2), spatial distance effects emerged at the ADJ region. We think that in this case participants did not process in-depth the already-seen noun phrases and that the adjective was then the first word to guide attention to relevant visual context representations.

An alternative possibility is that the pre-activated spatial distance representations activate semantic similarity even before participants read the sentence. However, if this were the case for the present experiments, then we should have seen more immediate effects of spatial distance (consistently in first pass times). In Experiment 2 in particular, when the cards on critical trials were blank and participants learnt the noun pairs minutes before sentence reading, we should have seen more early top-down effects of the visual context in first pass times. This was not the

case, suggesting that instead semantic interpretation of the sentence guided participants' attention to relevant aspects of the visual context representations.

With respect to the second issue (how spatial distance representations are co-indexed with semantic representations), the present findings permit us to refine the co-indexing mechanism in the Coordinated Interplay Account. Co-indexing of card distance and semantic similarity could happen in several ways. As a first possibility, the two noun phrases could be directly co-indexed with the cards. This appears plausible when the cards present the first two sentential nouns as was the case in Experiment 1. Alternatively, the spatial representation of object distance is co-indexed with the abstract semantic representation of similarity, implied by the two NPs and conveyed by the ADJ. In the latter case, co-indexing would not occur between the two cards and the corresponding *and*-coordinated NPs but rather between the representations activated by the cards in the visual context and those activated by the unfolding sentence interpretation.

A refined co-indexing mechanism that also allows conceptual (non-referential) mapping between language and visual context could accommodate effects of spatial distance on sentence interpretation even in the absence of *and*-coordination. This idea fits with the emergence of spatial distance effects at NP2 (Experiment 3) and also at sentence regions that do not imply semantic similarity (e.g., VP2 and NP3, 'said the professor' in Experiment 1). At NP2, semantic similarity is implied following the interpretation of the two noun phrases, suggesting that direct reference from a single lexical item to aspects of the visual context is not necessary for co-indexing. At the later sentence regions (VP2 and NP3), semantic similarity is not conveyed; however, the initial sentence is a relative clause to the sentence-final region 'said the professor'. Its content thus depends from the super-ordinate clause and may well be re-activated for that

reason during the super-ordinate clause, eliciting the extended spatial distance effects on semantic similarity or dissimilarity that we observed.

The idea of a non-referential co-indexing mechanism could further be tested by changing the structure of the sentences (e.g., NP-V-NP instead of NP-and-NP). If co-indexing of the card representations to the co-ordinated nouns is essential for the rapid spatial-distance effects that we observed, then these effects should be eliminated when we break up the correspondence of jointly moving cards and corresponding coordinated noun phrases by changing the sentence structure to NP-V-NP. By contrast, if this correspondence is non-essential, then we should replicate rapid spatial distance effects on semantic interpretation even when the cards remain coordinated (through their joint movement) but the noun phrases are not. In fact, recent results from our laboratory suggest that spatial distance between cards affects real time semantic interpretation in other semantic domains and even in the absence of *and*-coordinated noun phrases (Guerra & Knoeferle, 2014).

Together the results from these three experiments are the first evidence for rapid effects of non-referential spatial information on the incremental comprehension of abstract language. While these effects permit us to refine our insight into the time course of visually situated language comprehension when language is abstract and non-referential, one open issue is whether they implicate metaphorical mapping. A metaphorical mapping mechanism could potentially contribute towards forging the links from perceptual and motor experience to abstract conceptualization during conceptual learning and language acquisition (see Grady & Johnson, 1997; Johnson, 1999). Yet, the present study cannot distinguish whether we re-enact the metaphorical mapping between spatial distance and semantic similarity in real time every time we read about similarity, or whether we exploit instead pre-computed associations that originate

from metaphorical mapping. It is possible that such associations link spatial distance and semantic similarity. However, we have argued that our results cannot be explained in terms of lexical-semantic associations alone. Similarly we acknowledge that, in a more natural context, a reader may rarely see two unrelated objects moving apart or close together just before reading a sentence about similarity. The main insight from our results with regard to written sentence comprehension is that they show how language interpretation can be modulated by apparently unrelated visual information. We explored the relation between spatial distance and similarity, but further research could reveal the extent of non-referential visual context effects on reading.

We have further described how interpretation of the unfolding utterance can single out relevant spatial-distance representations that can then be co-indexed and inform the interpretation. Co-indexing thus implicates a one-to-one mapping (e.g., from a noun to an object, or from a verb to an action), but can also serve to relate abstract concepts of semantic similarity (that come about through compositional semantic interpretation) to representations of spatial information. The Coordinated Interplay Account enriched with these assumptions (a mapping from abstract nouns to non-linguistic representations of spatial distance; a co-indexing mechanism that is not just referential) can accommodate the real-time effects that we observed.

6. Conclusion

The results presented in this paper extend previous findings of spatial distance effects on similarity ratings (Casasanto, 2008) and response times (Boot & Pecher, 2010) to incremental language processing. They also provide strong evidence for the role of spatial information in abstract language comprehension in agreement with theories of grounded cognition (see Lakoff & Johnson, 1999). These findings are further compatible with the view that relations between non-linguistic and linguistic stimuli, which might have emerged during language acquisition

through metaphorical mapping (see Grady & Johnson, 1997; Johnson, 1999), contribute towards

incremental language processing. Rapid and incremental non-linguistic effects on abstract

language comprehension were observed beyond referential or lexical-semantic associative links.

Finally, our findings support the view that visually-derived perceptual information (i.e. spatial

distance between objects) contributes to the construction of meaning during real-time language

comprehension.

7. Acknowledgements

APPENDIX A

Critical sentences: 48 experimental sentences, each with two versions; either expressing dissimilarity (a) or similarity (b) between two abstract nouns.

1. a) Souveränität und Unsicherheit sind geradezu umgekehrt, so argumentierte die Denkerin.
   b) Verlegenheit und Unsicherheit sind ziemlich einheitlich, so argumentierte die Denkerin.
2. a) Munterkeit und Mattigkeit sind geradezu umgekehrt, so begründete die Logopädin.
   b) Ermüdung und Mattigkeit sind ziemlich einheitlich, so begründete die Logopädin.
3. a) Hochverrat und Loyalität sind geradezu umgekehrt, das behauptete die Fußballspielerin.
   b) Ergebenheit und Loyalität sind ziemlich einheitlich, das behauptete die Fußballspielerin.
4. a) Fortuna und Unglück sind sicher ungleich, so ersann der Clown.
   b) Unheil und Unglück sind gewiss verwandt, so ersann der Clown.
5. a) Ignoranz und Vorgefühl sind bestimmt verschieden, so träumte das Medium.
   b) Vorahnung und Vorgefühl sind freilich entsprechend, so träumte das Medium.
6. a) Frieden und Krieg sind bestimmt verschieden, das verriet der Anthropologe.
   b) Kampf und Krieg sind freilich entsprechend, das verriet der Anthropologe.
7. a) Werktag und Ruhepause sind sicher ungleich, das beschwur der Arbeiter.
   b) Atempause und Ruhepause sind gewiss verwandt, das beschwur der Arbeiter.
8. a) Ohnmacht und Können sind bestimmt verschieden, das verkündete der Artist.
   b) Talent und Können sind freilich entsprechend, das verkündete der Artist.
9. a) Freudenruf und Wutanfall sind sicher ungleich, so bekundete der Boxer.
   b) Zornausbruch und Wutanfall sind gewiss verwandt, so bekundete der Boxer.
10. a) Betrug und Benehmen sind eher andersartig, so verkündigte der Polizeibeamte.
    b) Anstand und Benehmen sind fast äquivalent, so verkündigte der Polizeibeamte.
11. a) Dummheit und Weisheit sind bestimmt verschieden, das erklärte der Professor.
    b) Begabung und Weisheit sind freilich entsprechend, das erklärte der Professor.
12. a) Lebensfreude und Traurigkeit sind geradezu umgekehrt, so tönte die Dichterin.
    b) Melancholie und Traurigkeit sind ziemlich einheitlich, so tönte die Dichterin.
13. a) Frohsinn und Trübsinn sind geradezu umgekehrt, so empfahl die Frau.
    b) Schwermut und Trübsinn sind ziemlich einheitlich, so empfahl die Frau.
14. a) Diebstahl und Bezahlung sind geradezu umgekehrt, so schrie die Gewerkschaftlerin.
    b) Vergütung und Bezahlung sind ziemlich einheitlich, so schrie die Gewerkschaftlerin.
15. a) Verstimmung und Wohlbefinden sind eher andersartig, so ließ die Kinderärztin verlauten.
    b) Zufriedenheit und Wohlbefinden sind fast äquivalent, so ließ die Kinderärztin verlauten.

16. a) Infektion und Gesundung sind geradezu umgekehrt, so dachte die Krankenschwester.

    b) Genesung und Gesundung sind ziemlich einheitlich, so dachte die Krankenschwester.

17. a) Betrübnis und Euphorie sind eher andersartig, so antwortete die Lehrerin.

    b) Entzücken und Euphorie sind fast äquivalent, so antwortete die Lehrerin.

18. a) Trennung und Heirat sind geradezu umgekehrt, so beurteilte die Organisatorin.

    b) Hochzeit und Heirat sind ziemlich einheitlich, so beurteilte die Organisatorin.

19. a) Minorität und Majorität sind eher andersartig, das erkannte die Präsidentin.

    b) Übermacht und Majorität sind fast äquivalent, das erkannte die Präsidentin.

20. a) Unwohlsein und Wohlgefühl sind eher andersartig, so erwiderte die Psychologin.

    b) Wohlbehagen und Wohlgefühl sind fast äquivalent, so erwiderte die Psychologin.

21. a) Bestrafung und Belohnung sind eher andersartig, das bestätigte die Richterin.

    b) Besoldung und Belohnung sind fast äquivalent, das bestätigte die Richterin.

22. a) Kräftigkeit und Schwachheit sind eher andersartig, das beteuerte die Sportlehrerin.

    b) Ermattung und Schwachheit sind fast äquivalent, das beteuerte die Sportlehrerin.

23. a) Aufregung und Entspannung sind eher andersartig, das bekräftigte die Therapeutin.

    b) Erholung und Entspannung sind fast äquivalent, das bekräftigte die Therapeutin.

24. a) Feindschaft und Kameradschaft sind eher andersartig, das enthüllte die Beraterin.

    b) Partnerschaft und Kameradschaft sind fast äquivalent, das enthüllte die Beraterin.

25. a) Zustimmung und Widerspruch sind bestimmt verschieden, so entschied der Lehrer.

    b) Opposition und Widerspruch sind freilich entsprechend, so entschied der Lehrer.

26. a) Illusion und Gewissheit sind bestimmt verschieden, das erzählte der Wissenschaftler.

    b) Tatbestand und Gewissheit sind freilich entsprechend, das erzählte der Wissenschaftler.

27. a) Leid und Glanz sind eher andersartig, das äußerte das Fotomodell.

    b) Ruhm und Glanz sind fast äquivalent, das äußerte das Fotomodell.

28. a) Abneigung und Zuneigung sind sicher ungleich, so meinte der Großvater.

    b) Zuwendung und Zuneigung sind gewiss verwandt, so meinte der Großvater.

29. a) Konflikt und Einigung sind bestimmt verschieden, das fand der Historiker.

    b) Eintracht und Einigung sind freilich entsprechend, das fand der Historiker.

30. a) Rückzug und Offensive sind sicher ungleich, so brüllte der Infanterist.

    b) Feldzug und Offensive sind gewiss verwandt, so brüllte der Infanterist.

31. a) Faktum und Märchen sind bestimmt verschieden, so las der Journalist.

    b) Fiktion und Märchen sind freilich entsprechend, so las der Journalist.

32. a) Unbegabtheit und Kreativität sind geradezu umgekehrt, so korrigierte die Wahrsagerin.

    b) Genialität und Kreativität sind ziemlich einheitlich, so korrigierte die Wahrsagerin.

33. a) Humor und Trauer sind eher andersartig, so deklarierte das Mädchen.

    b) Kummer und Trauer sind fast äquivalent, so deklarierte das Mädchen.

34. a) Jammer und Pracht sind bestimmt verschieden, das glaubte der Mann.

b) Luxus und Pracht sind freilich entsprechend, das glaubte der Mann.

35. a) Gewinn und Verlust sind sicher ungleich, so zeterte der Politiker.

    b) Schaden und Verlust sind gewiss verwandt, so zeterte der Politiker.

36. a) Hochgefühl und Höllenangst sind bestimmt verschieden, so rezitierte der Poet.

    b) Herzensangst und Höllenangst sind freilich entsprechend, so rezitierte der Poet.

37. a) Friedsamkeit und Zwietracht sind geradezu umgekehrt, das rief die Priesterin.

    b) Streiterei und Zwietracht sind ziemlich einheitlich, das rief die Priesterin.

38. a) Übereinkunft und Kampfhandlung sind bestimmt verschieden, das sagte der Soldat.

    b) Konfrontation und Kampfhandlung sind freilich entsprechend, das sagte der Soldat.

39. a) Dissonanz und Wohlklang sind sicher ungleich, das bejahte der Sänger.

    b) Wohllaut und Wohlklang sind gewiss verwandt, das bejahte der Sänger.

40. a) Glück und Sorge sind sicher ungleich, das schrieb der Schauspieler.

    b) Angst und Sorge sind gewiss verwandt, das schrieb der Schauspieler.

41. a) Fairness und Mogelei sind sicher ungleich, das weissagte der Schiedsrichter.

    b) Gaunerei und Mogelei sind gewiss verwandt, das weissagte der Schiedsrichter.

42. a) Antipathie und Liebelei sind eher andersartig, das stellte der Schreiber fest.

    b) Romanze und Liebelei sind fast äquivalent, das stellte der Schreiber fest.

43. a) Arbeitszeit und Vergnügen sind sicher ungleich, das suggerierte der Unterhalter.

    b) Unterhaltung und Vergnügen sind gewiss verwandt, das suggerierte der Unterhalter.

44. a) Verachtung und Verehrung sind bestimmt verschieden, so vermutete die Dame.

    b) Ehrfurcht und Verehrung sind freilich entsprechend, so vermutete die Dame.

45. a) Belobigung und Entwürdigung sind geradezu umgekehrt, das verteidigte die Soziologin.

    b) Erniedrigung und Entwürdigung sind ziemlich einheitlich, das verteidigte die Soziologin.

46. a) Vergötterung und Nichtbeachtung sind geradezu umgekehrt, das zeigte die Nonne.

    b) Geringachtung und Nichtbeachtung sind ziemlich einheitlich, das zeigte die Nonne.

47. a) Achtsamkeit und Zerstreutheit sind sicher ungleich, das teilte der Psychiater mit.

    b) Zerfahrenheit und Zerstreutheit sind gewiss verwandt, das teilte der Psychiater mit.

48. a) Mittellosigkeit und Besitzlosigkeit sind sicher ungleich, so berichtigte der Wirtschafter.

    b) Wohlhabenheit und Besitzlosigkeit sind gewiss verwandt, so berichtigte der Wirtschafter.

APPENDIX B

Table B1: Results of the 2 x 2 repeated-measures ANOVA analyses for regions on which linear mixed-effect analyses resulted in an interaction effect (*F1: df*2 = 45(46 for Experiment 2) for F1; *F2: df*2 = 31 for F2; *df*1 = 1)

Experiment	Region	Measure	Predictor	F1	η^2	F2	η^2
Experiment 1	ADJ	First-pass	Similarity	16.23 ***	0.344	8.960 **	0.166
			Distance	1.834	0.044	0.280	0.006
			S x D	3.604 #	0.105	7.529 **	0.143
	VP2	First-pass	Similarity	3.181 #	0.084	5.488 *	0.111
			Distance	2.164	0.151	0.693	0.016
			S x D	3.758 #	0.108	3.485 #	0.073
	NP3	First-pass	Similarity	0.145	0.005	1.162	0.025
			Distance	7.698 **	0.199	1.335	0.029
			S x D	4.531 *	0.128	3.009 #	0.063
	NP3	Total times	Similarity	1.517	0.047	2.522	0.053
			Distance	3.149 #	0.092	0.271	0.006
			S x D	6.481 *	0.173	3.306 #	0.068
Experiment 2	ADJ	Regression path	Similarity	5.688 #	.155	3.876 #	.078
			Distance	0.672	.021	0.347	.007
			S x D	4.126 #	.117	3.710 #	.075
	ADJ	Total times	Similarity	3.639 *	.105	1.174	.025
			Distance	2.641	.079	1.284	.027
			S x D	7.752 **	.200	4.904 *	.096
Experiment 3	NP2	First-pass	Similarity	15.020 ***	0.326	2.512	0.053
			Distance	1.232	0.038	0.971	0.021
			S x D	2.015	0.061	7.537 **	0.143
	VP2	First-pass	Similarity	0.018	0.001	0.098	0.002
			Distance	0.142	0.005	0.018	0.000

S x D	4.757 [*]	0.133	2.050	0.045

Note: $p<0.1 = \#$, $p<0.05 = *$, $p<0.01 = **$, $p<0.001 = ***$

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