Saccade trajectories reveal dynamic interactions of semantic and spatial information during the processing of implicitly spatial words

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Abstract

Implicit up/down words, such as *bird* and *foot*, systematically influence performance on visual tasks involving immediately following targets in compatible vs. incompatible locations. Recent studies have observed that the semantic relation between prime words and target pictures can strongly influence the size and even the direction of the effect: Semantically related targets are processed faster in congruent vs. incongruent locations (location-specific priming), whereas unrelated targets are processed slower in congruent locations. Here, we used eye-tracking to investigate the moment-to-moment processes underlying this pattern. Our reaction time results for related targets replicated the location-specific priming effect and showed a trend towards interference for unrelated targets. We then used growth curve analysis to test how up/down words and their match vs. mismatch with immediately following targets in terms of semantics and vertical location influences concurrent saccadic eye movements. There was a strong main effect of spatial association on linear growth with up words biasing changes in y-coordinates over time upwards relative to down words (and vice versa). Similar to the RT data, this effect was strongest for semantically related targets and reversed for unrelated targets. Intriguingly, all conditions showed a bias in the congruent direction in the initial stage of the saccade. Then, at around halfway into the saccade the effect kept increasing in the semantically related condition, and reversed in the unrelated condition. These results suggest that online processing of up/down words triggers direction-specific oculomotor processes that are dynamically modulated by the semantic relation between prime words and targets.

Key words: Conceptual processing; eye-tracking; spatial attention

Introduction

Language comprehension involves the rapid and efficient retrieval of relevant multimodal information about word referents (Binder & Desai, 2011; Fernandino, Humphries, Conant, Seidenberg, & Binder, 2016; Fernandino et al., 2016b). A question of intense debate in recent years has been whether and to what extent modality-specific sensory-motor systems are used as a source of information during conceptual processing (Barsalou, 2016; Binder, 2016; Binder & Desai, 2011; Mahon, 2015; Mahon & Caramazza, 2008; Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012). Regarding concrete concepts, whose referents possess a reliable set of perceptual features, there is evidence suggesting that information about object shape (Lewis & Poeppel, 2014; Ostarek & Huettig, 2017a, 2017b), motion (Meteyard, Bahrami, & Vigliocco, 2007; Meteyard, Zokaei, Bahrami, & Vigliocco, 2008; van Dam, Speed, Lai, Vigliocco, & Desai, 2017), color (Simmons et al., 2007), and associated actions (Beauchamp & Martin, 2007; Chao, Haxby, & Martin, 1999; Hauk, Johnsrude, & Pulvermüller, 2004; Martin, 2007; Pulvermüller, 2005; Shtyrov, Butorina, Nikolaeva, & Stroganova, 2014; Vukovic, Feurra, Shpektor, Myachykov, & Shtyrov, 2017) is retrieved from the corresponding modal systems. Recent studies have indicated that access to sensory processes during conceptual processing is highly task-dependent (Hoenig, Sim, Bochev, Herrnberger, & Kiefer, 2008; Kemmerer, 2015; Lebois, Wilson-Mendenhall, & Barsalou, 2015; Ostarek & Huettig, 2017a; Rommers, Meyer, & Huettig, 2013; van Dam, van Dijk, Bekkering, & Rueschemeyer, 2012; Yee & Thompson-Schill, 2016), a property that is likely owed to the highly context-dependent mapping between words and conceptual representations (Barsalou, 1983, 1993; Thomson & Tulving, 1970) and to a division of labor between low-level and high-level systems (Barsalou, 2016; Binder, 2016; Borghesani et al., 2016; Borghesani & Piazza, 2017; Chen, Ralph, & Rogers, 2017; Fernandino et al., 2016a; Fernandino et al., 2016b; Pobric, Ralph, & Jefferies, 2009; Ralph, 2014; Ralph, Jefferies, Patterson, & Rogers, 2016; Rogers et al., 2004).

The rigorous examination of the mechanisms involved in promising experimental paradigms tapping conceptual representation proved to be critical to allow the field to ask more and more detailed questions, but it can also dampen initial excitement when the story is more complicated than a first look suggested. A point in case is the study of verbs implying upward or downward motion (such as *rise* and *fall*). Initially, Meteyard et al. (2007) showed that such verbs induce increased sensitivity at detecting near-threshold motion of dot patterns in congruent direction. A subsequent study went a step further by showing that, conversely, near-threshold motion patterns interfered with lexical decisions on incongruent verbs, suggesting a causal role of low-level visual processes in verb comprehension (Meteyard et al., 2008). However, recent functional magnetic resonance imaging (fMRI) studies localized the direction-specific congruency effect of verbs on motion perception to the left middle temporal gyrus implicated with high-level conceptual processing and found no evidence that these verbs activated motion-sensitive visual areas (Francken, Kok, Hagoort, & De Lange, 2014; Francken, Meijs, Hagoort, Van Gaal, & De Lange, 2015). Moreover, the congruency effect persisted when prime words were presented subliminally, suggesting that it does not rely on feedback to visual areas (Francken, Meijs, Ridderinkhof, et al., 2015). At the same time, studies looking at sentences (Saygin, McCullough, Alac, & Emmorey, 2010) and narratives (Wallentin et al., 2011) about motion did find increased activation levels in the motion-selective region MT/V5, suggesting that richer contexts may be more likely to recruit featural information from sensory cortex. Thus, more research is required to elucidate when motion language recruits motion-sensitive visual processes.

Research in a related paradigm investigating the effects of words/sentences with up vs. down associations on visual categorization and detection has gone through a similar refinement process. Bergen, Lindsay, Matlock, and Narayanan (2007) first reported that up/down sentences (such as *the ground/roof shook*) interfered with the subsequent identification of a circle vs. a square in congruent location. Further studies extended the interference effect to single nouns (Estes, Verges, & Barsalou, 2008; Verges & Duffy, 2009) and verbs (Verges & Duffy, 2009). These findings were interpreted as evidence that location-specific visual simulations of the denoted referents interfered with concurrent perceptual processing of the targets, as proposed by Barsalou and colleagues (Barsalou, 1999, 2008; Barsalou, Simmons, Barbey, & Wilson, 2003).

Several subsequent studies observed facilitation instead of interference for targets in compatible location using very similar paradigms (Dudschig, Lachmair, de la Vega, De Filippis, & Kaup, 2012; Gozli, Chasteen, & Pratt, 2013; Gozli, Pratt, Martin, & Chasteen, 2016; Zhang et al., 2013). In a series of experiments, Gozli et al. (2013) singled out the factors driving the direction of the effect and concluded that interference is likely to be observed at short stimulus onset asynchronies (SOAs) between cue word and target (< 400 ms) and when discrimination (as opposed to detection) tasks are used, whereas facilitation is typically obtained at longer SOAs or when detection tasks are used. Finally, recent studies showed that the usually observed interference in compatible location at short SOAs can be turned into facilitation when the target is semantically related to the prime word (Estes, Verges, & Adelman, 2015; Ostarek & Vigliocco, 2017).

One account that has been brought forth to explain this set of findings rests on the notion of situated conceptualization. According to that framework, even single words evoke rich knowledge of events in which their referents are typically perceived (Barsalou, 2003; Barsalou, 2009). The role of SOA can be captured by a basic simulation explanation, as interference is only expected during semantic processing when visual simulation is expected to hinder simultaneous visual processing of the target, whereas residual activation of spatial representations can account for late facilitation. Critically, the account can explain the location-specific facilitation effect for semantically related targets by assuming that related targets benefit from the prime because they can be integrated in the activated (location-specific) event, whereas unrelated targets cannot (Ostarek & Vigliocco, 2017).

Two accounts have recently been proposed to complement the situated conceptualization explanation. The perceptual matching account proposes that participants engage in a form of automatic visual search behavior and implicitly code targets for congruence vs. incongruence in terms of their identity and location, and that conflicting codes produce interference (Estes et al., 2015). It is based on evidence from eye-tracking studies that words trigger a visual search for a corresponding (or related) target (see Huettig, Olivers, & Hartsuiker, 2011, for discussion), which has been suggested to be automatic because it even occurs word cues are irrelevant for the task (Spivey, Tyler, Eberhard, & Tanenhaus, 2001). The rationale is that inconsistent codes constitute ambiguous evidence for whether the target is the word referent or not: An unrelated target appearing in a compatible location provides evidence that it may be the word referent, which then has to be ruled out before the identity of the actual target is established. Conversely, when an unrelated target appears in an incompatible location, there is no evidence that it is the referent to begin with and its identity can be processed immediately. Finally, when a related target appears in a compatible location, a match in terms of both location and object constitutes useful evidence that the target is the referent. Apart from being quite post-hoc, the perceptual matching account does not predict the finding that semantically related, but perceptually dissimilar, targets elicit facilitation at short SOAs (Ostarek & Vigliocco, 2017). Moreover, it does not speak to the mechanisms by which location and object codes are generated. In fact, it is conceivable that matching of location and identity codes is done by comparing location and object features of the visual targets with the content of simulated events, in which case perceptual matching can be considered as a paradigm-specific consequence of situated conceptualization.

Two recent studies (Amer, Gozli, & Pratt, 2017; Gozli et al., 2013) suggested an alternative account based on the theory of event coding (TEC) whose central tenet is that perceptual and action-related features belonging to the same event are temporarily bound into a short-lived event file (Amer et al., 2017; Hommel, 1998, 2004; Rothermund, Wentura, & De Houwer, 2005). Assuming that conceptual processing involves sensorimotor systems, the TEC can indeed be successfully applied to the spatial cuing paradigm: It correctly predicts interference at short SOAs when a stimulus feature that is hypothesized to be bound (e.g., the semantic feature "up" of a word) is required for the visual task (e.g., when the target appears at the top of the screen), and it correctly predicts facilitation at long SOAs (due to pre-activation) when features are expected to no longer be bound. Similarly, the finding that semantically related words shorten RTs to targets in compatible location only (Estes et al., 2015; Ostarek & Vigliocco, 2017) can be ascribed to the ability to integrate the picture features with the event file activated by the word.

In the present study, we used eye-tracking to investigate how the cognitive mechanisms underlying the location-specific priming vs. interference effects unfold from the moment the prime word is presented until the target picture is fixated. Previous studies used RT measures that are blind to the online cognitive processes that unfold as congruence vs. incongruence on multiple levels interacts and only give one piece of discrete information about their final outcome. Eye-tracking, by contrast, can reveal the dynamically emerging processes with the highest temporal resolution.

Recent eye-tracking studies found that processing up/down words can shorten launch times for saccades in compatible direction (Dudschig, Souman, Lachmair, de la Vega, & Kaup, 2013; Dunn, 2016). However, these studies used a paradigm in which participants performed a lexical decision task by moving their eyes up vs. down, which makes the link of the results to semantic processing unclear because, by the very nature of the task, semantic processing was likely completed by the time participants started moving their eyes. This is because in order to make a lexical decision one must have first processed the word. The crucial test would be a situation in which semantic processing of up/down words occurs simultaneously with eye-movements. In the present study, we achieved this by minimizing the delay between word and visual target allowing us to study the direct effect of semantic processing on concurrent eye movements. We focused on saccade trajectories instead of launch times to investigate how the effects of implicitly spatial words unfold throughout the saccade and how they interact with spatial and semantic properties of the targets across time.

The present study

In the present study, we used a design similar to a recent study (Ostarek & Vigliocco, 2017) that looked into the role of the semantic relation between cue words and target pictures on the spatial congruency effect. The design is different from the one usually used in spatial cuing paradigms in that the targets are not meaningless symbols (such as X vs. O), but drawings of objects that are either semantically related or unrelated to the prime word. The motivation for choosing this paradigm was three-fold: 1) Both the situated conceptualization and TEC account assume that sensory processes are activated to provide semantic information about spatial location, however to date there is not strong evidence for that claim. Previous studies observed shortened saccade launch times right after up/down words were processed (Dudschig et al., 2013; Dunn, 2016). We go one step further by testing whether up/down word processing biases *concurrent* saccade trajectories up/down, as this would indicate that semantic processing of up/down words involves direction-sensitive representations in the oculomotor network. 2) On the behavioral level, we wanted to see whether we could replicate the finding that semantic relatedness of cue and target can turn the usually observed interference effect at short SOAs into facilitation (Ostarek & Vigliocco, 2017). This pattern is predicted by situated conceptualization accounts because processing of semantically related targets in compatible locations is expected to benefit from the situated simulation triggered by the prime word. TEC would also be compatible with this outcome if one assumes that prime-target pairs with semantic feature overlap can be integrated in a single event file whereas prime-target pairs with non-overlapping features cannot. 3) Most importantly, we wanted to investigate to what extent this pattern is reflected in saccade trajectories, i.e. to observe potential facilitation or interference effects emerge and unfold on a moment-to-moment basis. One main hypothesis was that saccade trajectories would be biased towards the direction associated with the prime word at early stages of the saccade, in line with simulation-based accounts of situated conceptualization. Furthermore, TEC predicts additional modulations of saccade trajectories depending on the semantic relation of the prime word and target. In particular, saccades towards spatially and semantically congruent targets should be facilitated, whereas saccades towards targets that are only congruent on one domain (spatial or semantic) should be hindered. This is because spatial and semantic features activated by the prime words are assumed to be temporarily bound in an event file. Therefore, when one of the features is required for processing of the target it first has to be separated from the event file evoked by the word and then incorporated into a new event file (Hommel, 1998, 2004).

Method

Participants

We tested 57 healthy participants (35 female, 10 left-handed, mean age: 26.8) from the local MPI subject database. Two participants had to be excluded because their vision was impaired, one because of a technical error, and two because calibration failed. All analyses were performed on the data from the remaining 52 participants who all had normal or corrected-to-normal vision (contact lenses were allowed). They gave written consent and were paid six euros for their participation. We had ethics approval for the study from the faculty for Social Sciences of Radboud University Nijmegen.

Set-up, Materials, and Procedure

We recorded eye-movements with a tower-mount Eye-Link 1000 eye-tracker (SR Research) with 1000 Hz temporal resolution. The experiment was programmed and run in Experiment Builder (SR Research). The session began with a standard nine-point calibration procedure. Participants placed their head on a chin rest 70 cm from the screen (1920x1080, 60Hz) and were asked to keep their head still during the experiment.

There were a total of 224 trials (see Figure 1) broken down into eight blocks such that participants had a chance to take a brief break every 28 trials. At the beginning of every block, a fixation dot appeared at the center of the screen that served as drift correction. Once the dot was fixated by the participant, the researcher confirmed correct fixation by pressing enter which resets the current fixation location as center of the screen. Each trial began with a central fixation cross displayed for 500ms, followed by a central prime word (100ms), a blank screen (50ms), and finally the target. This quick succession of events made it possible to study the effect of online word processing on saccade trajectories. In particular, the visual target appeared just 150ms after word onset (and 50ms after word offset) and was expected to rapidly trigger a saccade that should land on the target some hundreds of milliseconds later. Thus, the saccade was expected to occur in the time window typically associated with semantic processing.

[Figure 1 around here]

The targets were line drawings of objects (n=28) or geometric shapes (n=28) and were presented four times each; twice at the top of the screen and twice at the bottom. Every line drawing was paired with one semantically related up/down word, one unrelated up word, one unrelated down word, and one spatially neutral control word, which were all presented once[1]. The geometric shapes were paired with the same set of words. We counterbalanced target location (top vs. bottom) between subjects such that every word was followed by the corresponding targets at the top vs. bottom of the screen equally often.

22 separate subjects that did not participate in the main experiment rated all words on a 7-point Likert scale ranging from 1 (object is always seen low in the visual field) to 7 (object is always seen high in the visual field). Non-parametric Wilcoxon signed rank tests showed that up words (median=5.25, SD=0.66) were rated to have a significantly stronger up association (estimate=3.50, 95% CIs: 3.12, 3.88, p<0.001) compared to down words (median=2, SD=0.54), and both differed significantly from the neutral control words (median=4, SD=0.50; up vs. control: estimate=1.87, 95% CIs: 1.50, 2.13, p<0.001; down vs. control: estimate=1.75, 95% CIs: 1.38, 2.00, p<0.001). The different prime types (semantically related up words, semantically related down words, unrelated up words, unrelated down words, and spatially neutral control words) were matched (all pairwise comparisons; p>0.05) for frequency (using log word frequency in the SUBTLEX databse; Keuleers, Brysbaert, & New, 2010), age of acquisition (Brysbaert, Stevens, De Deyne, Voorspoels, & Storms, 2014), number of letters, and number of syllables (see Appendix). Latent semantic similarity analysis (Landauer, Foltz, & Laham, 1998) was used to quantify semantic similarity between the prime words and target pictures across conditions and showed that the semantically related condition had significantly higher cosines than the control condition (p<0.001) and the unrelated condition (p<0.001), whereas there was no significant difference between the control and unrelated condition (p>0.2). Finally, up-down ratings were not different in the related vs. unrelated condition (p>0.05) and thus effects of prime type cannot be attributed to confounds in spatial association.

[1] with the exception of one unrelated up word and one unrelated down word that were presented twice

Participants had to decide as quickly and as accurately as possible whether they saw an everyday object or a geometric shape by pressing the left or right button of a button-box (counterbalanced across participants). As soon as participants responded, the trial ended with a 500ms blank screen after which the next fixation cross appeared. The everyday object vs. geometric shape task was chosen for two reasons: 1) Previous data indicate that congruency effects in the spatial cueing paradigm may depend on target features, especially the extent to which semantic features are shared between prime and target. At short SOAs, up/down words tend to have an interference effect on the identification of simple meaningless targets (such as single letters) in compatible location (Estes et al., 2015, 2008; Gozli et al., 2013), whereas a facilitation effect was observed on semantically related pictures (Estes et al., 2008; Ostarek & Vigliocco, 2017), and no location-specific effect was observed on unrelated pictures (Ostarek & Vigliocco, 2017). Our design allowed us to test the role of the type of prime-target relation on the spatial congruency effect within a single experiment. 2) As we used a variety of geometric shapes, participants were required to look at the targets in order to accurately perform the task.

Analysis

RT data

RT data were trimmed by removing erroneous trials, responses faster than 300ms or slower than 2.5s (which are unlikely to be voluntary responses related to the task), and responses that were more than 2.5 standard deviations from the grand mean per condition. Scaled RTs were used for analysis.

We assessed the effects of Prime Target Relation (semantically related, unrelated, geometric shape) and Spatial Congruence (congruent vs. incongruent) as well as their interaction using a linear mixed effects model (lme4 package) with per-participants and per-target item intercepts as well as random by-participants and by-target item slopes for Prime Target Relation and Spatial

Congruence. A model including random slopes for the interaction term did not converge. Likelihood ratio tests were used to test for significant main effects and interactions by comparing a model including the factor/interaction of interest with one that did not include it but was otherwise identical. To follow up significant interaction effects, we used lsmeans for pairwise comparisons of the effect of Spatial Congruence at all Prime-Target Relation levels (lsmeans package; Lenth, 2016).

Eye-tracking data

With respect to the eye-tracking data, we hypothesized that up/down words differentially influence saccade trajectories and that this effect should interact with the relation between prime word and target picture. To test this hypothesis we used growth curve analysis (GCA; Mirman, Dixon, & Magnuson, 2008) implemented in the psy811 package to analyze changes in y-coordinates over time. In particular, the dataset was organized such that for every participant there was one data point (y-coordinate in pixels) per condition per ms to which a first-degree polynomial (linear term) was fitted, which was then submitted to a linear mixed effects model including Spatial Association of Prime (up vs. down), Prime-Target Relation (semantically related vs. unrelated vs. geometric shape), the linear term, and all interaction terms as fixed effect and per-participants random intercepts (more complex models with random slopes did not converge).

We analyzed the data from the moment the prime word appeared (500ms into the trial) until the saccade landed on the target (1250ms)[2]. There were two key predictions: 1) An effect of Spatial Association of Prime on the linear term. This would indicate that up vs. down words have differential effects on the slopes of saccade trajectories, meaning that differences in y-coordinates due to the words' spatial associations grow stronger over time (see Mirman et al.,

[2] This number was derived from visual inspection of Figures 3 and 4 and reflects the point of inflection where on average the trajectories stopped rising or falling.

2008). We expected that up words would bias the slope of the trajectory upwards relative to down words (and vice versa). As the slopes describe the rate of change in y-coordinates over time, they directly reflect the speed of saccades. Effects on the linear term can therefore be thought of as consistent effects on saccade velocities across time. 2) An interaction effect of Spatial Association of Prime and Prime-Target Relation on the linear term such that words would speed up saccades towards the associated location when the target is semantically related and slow down saccades towards the associated location when the target is semantically unrelated.

Results

RT data

The linear mixed effects model on the RT data (see Figure 2) showed no main effect of Spatial Congruence and a small effect of Prime-Target Relation with slightly faster responses to geometric shapes compared to the unrelated condition (estimate=-0.071, SE=0.035, t=-2.012, p=0.044). Importantly, there was an interaction of Spatial Congruence and Prime-Target Relation (Chisq(2)=9.873, p=.007) that was characterized by the pattern that in the semantically related condition RTs were significantly shorter for spatially congruent vs. incongruent targets (lsmeans estimate=-.130, SE=.052, t-ratio=-2.491, p=.015) whereas in the unrelated and geometric shape conditions RTs were slower for spatially congruent targets. However, this effect was only marginally significant for unrelated pictures (estimate=.059, SE=.035, t-ratio=1.701, p=.091), and non-significant for geometric shapes (estimate=.043, SE=.029, t-ratio=1.482, p=.142).

[Figure 2 around here]

We thus replicated the location-specific priming effect (Ostarek & Vigliocco, 2017); RTs to trials of the type ["sky" --> picture of a cloud at the top] are fastest, whereas RTs to ["sky" --> picture of a cloud at the bottom] are slowest despite the semantic relationship between prime and target that typically yields facilitation when the spatial location is not manipulated. Furthermore, as in our previous study (Ostarek & Vigliocco, 2017), we only obtained a non-significant trend towards interference for unrelated targets in congruent location. One possible explanation is that studies that found the interference effect used very simple meaningless targets (Estes et al., 2015, 2008; Gozli et al., 2013) and that the RT data reflect a mixture of facilitation due to spatial congruence and interference due to semantic incongruence, a point to which we will return in the Discussion.

Eye-tracking data

In terms of the saccade trajectories, the main question was whether up/down word processing would have a direction-specific impact on simultaneous saccades and how this effect would be modulated by the semantic relation with the target. Figures 3 and 4 show the effects of Spatial Association of Prime and Prime-Target Relation on upward and downward saccades respectively. The lines were corrected for small baseline differences by subtracting the mean y-coordinates in the 500ms time window before the prime word appeared per condition. The vertical dotted lines represent prime word onset (at 500ms into the trial) and target picture onset (at 650ms). The plots suggest a large congruency effect in the semantically related condition, a smaller effect in the geometric shape condition, and no visible effect in the unrelated condition. Note that small differences may not be detectable in these plots as they show the entire eye-movement trajectories from the center to the top/bottom of the screen.

[Figures 3 and 4 around here]

To better visualize smaller effects over time, Figure 5 collapses across upwards and downwards saccades and shows the spatial congruency effect (i.e. the extent to which up words induce an upward bias in y-coordinates relative to down words (or vice versa)) in the three Prime-Target Relation conditions. As has been repeatedly reported in the literature, upwards saccades are launched and executed slightly faster than downwards saccades. To adjust for that we computed one grand mean y-coordinate per ms (the mean y-coordinate across all conditions) and subtracted it from the observed y-coordinates in all conditions (henceforth "normalized y-coordinate"), so as to conserve the relative differences between conditions whilst eliminating the bump created by overall quicker upward saccades. This was done to make the plot easier to read: If there was no effect the lines would be expected to stay flat at around zero. Instead, the figure suggests an increasing bias in the direction of the prime words' spatial associations as the saccade unfolds that seems to be strongest for semantically related targets and reversed for unrelated objects.

GCA was used to statistically quantify effects of Spatial Association of Prime and Prime-Target Relation on vertical saccade trajectories. It showed a strong effect of Spatial Association of Prime on the linear term with up words biasing saccades upwards relative to down words (estimate=26.693, SE=1.133, t=23.570, p<.001). Similar to the behavioral data, Spatial Association of Prime interacted with Prime-Target Relation (Chisquare(2)=568.08, p<.001) with a larger effect of Spatial Association of Prime on the linear term in the semantically related condition compared to the unrelated condition (estimate=31.111, SE=1.602, t=19.424, p<.001) and compared to the geometric shape condition (estimate=3.637, SE=1.602, t=2.271, p=0.023).

[Figure 5 around here]

Post-hoc tests looking at the effect of Spatial Association of Prime in all Prime-Target Relation conditions showed a large effect in the semantically related condition (estimate=61.440, SE=2.049, t=29.990, p<.001), a large effect in the geometric shape condition (estimate=23.056, SE=1.791, t=12.876, p<.001), and a small effect in the opposite direction in the unrelated condition (estimate=-4.418, SE=1.924, t=-2.296, p=.022). Figure 5 suggests that in the unrelated condition prime words initially have an effect in the congruent direction in the first third/half of the saccade that turns into a bias in the incongruent direction in the second half. To assess this statistically, we performed an exploratory follow-up analysis replacing the linear term with a quadratic term that should capture the bidirectional effect in the form of a significant negative effect of Spatial Association of Prime on the quadratic term, which is precisely what we found (estimate=-8.020, SE=1.892, t=-4.24, p<.001). An equivalent analysis for the geometric shape condition showed a non-significant trend towards a negative effect of Spatial Association of Prime on the quadratic term (estimate=2.483, SE=1.767, t=1.406, p=0.16), whereas in the semantically related condition there was a positive effect on the quadratic term (estimate=39.174, SE=4.12, t=9.509, p<.001) likely reflecting the initial dip followed by a growing increase.

These results suggest that implicitly spatial words have an initial automatic effect on concurrent saccades biasing them towards the congruent location, effectively speeding up saccades in the congruent direction and slowing down saccades in the incongruent direction. This effect can be either enhanced or reversed as the saccade unfolds depending on the relation of the word with the target. When the word and target are semantically related the initial congruency effect grows stronger over time until the saccade reaches its target. By contrast, when the target is an unrelated object, saccades in the congruent direction are slowed down as the eyes move towards the target.

It could be argued that including data points from the prime word onset until the saccade lands on the target might have contaminated the analysis with baseline differences before the saccades were initiated and with differences in target fixation after the saccade was completed. However, as can be seen in Figure 5, differences between conditions are very small in the short time-window prior to saccade onset. Nevertheless, we conducted an additional analysis restricted to the mean saccade onset until mean saccade offset (ca. 300ms after word onset until 700ms after word onset, 800-1200ms on Figures 3, 4, and 5). We found that the effect of Spatial Association of prime on the linear term remains significant (estimate=10.048, SE=1.245, t=8.07, $p<.001$), as does the interaction with Prime-Target Relation (Chisquare(2)=242.95, $p<.001$); again there was a larger effect of up vs down words on the linear term in the semantically related relative to the unrelated condition (estimate=22.607, SE=1.760, t=12.84, $p<.001$), however the comparison with the geometric shape condition was not significant (estimate=2.181, SE=1.760, t=1.12, $p>0.4$).

We next addressed a potential confound pertaining to the interaction effect. Because of the difficulty to come up with pictures that are semantically related to both up and down words (or vice versa), in our design, targets in the semantically related condition following up words ("up targets") are not the same as the ones following down words ("down targets"). It is thus possible that there are differences in the pictures themselves that influence saccade trajectories in a systematic way. Therefore we conducted a follow-up analysis that included the interaction of target type (up target vs. down target) and the linear term as additional fixed effect to account for the effect of low-level differences in the target images on saccade trajectories (we dropped geometric shape both in the Prime-Target Relation condition as well as in the Target Type condition because they could not be orthogonally crossed). The results showed that up targets indeed had a larger effect on the linear term compared to down targets (estimate=34.567, SE=0.792, t=43.648, p<.001). Crucially, the effect of Spatial Association of Prime on the linear term persisted (estimate=53.748, SE=4.747, t=11.32, p<.001), as did the interaction with Prime-Target Relation; related words have a much bigger effect on the linear term compared to unrelated words (estimate=63.327, SE=5.705, t=11.10, p<.001). This suggests that semantically related words exert a stronger influence on saccade trajectories congruent with their spatial association because of their relation with the target, not because of a low-level confound.

Discussion

In this study we set out to test the effect of words whose referents are typically observed up or down in space on concurrent eye movements. We did so by investigating whether processing such words impacts on saccade trajectories that have to be carried out in parallel, and we probed to what extent the relation between prime word and target picture has a modulatory effect, similar to what previous behavioral studies have observed (Estes et al., 2015; Ostarek & Vigliocco, 2017). Our two main findings were that 1) up/down words have a highly consistent effect on saccadic eye movements in the direction of their spatial associations and 2) the closer the eye gaze gets to the targets the stronger the semantic relation between primes and targets weighs in, an effect we attribute to increasingly foveal processing of the targets and the resulting increasing availability of semantic information.

More specifically, our results suggest that processing implicitly spatial words initially biases vertical saccade trajectories toward the direction congruent with the words' spatial association, regardless of what the target is. From about a third to halfway into the saccade, the nature of the target plays a major role such that semantically related targets trigger a further boost of the initial congruency effect, whereas unrelated targets turn the effect around and show a bias in the opposite direction until the saccade lands on the target. We suggest that this pattern is the eye-movement correlate of the location-specific priming effect observed in the RT data and that this is a prime example of eye-tracking permitting a glimpse into the moment-to-moment workings of the brain that RT data do not provide: Possibly the interference effect for unrelated targets in congruent location is small and therefore only sometimes observed (Estes et al., 2015, 2008; Gozli et al., 2013; Ostarek & Vigliocco, 2017) because it reflects two contrastive effects unfolding in time: Initial facilitation due to spatial congruence and subsequent interference due to semantic incongruence.

What is particularly striking is the short time-scale at which these complex cognitive processes occur. It has been clear from previous research that saccades are not entirely ballistic and can be modulated by the presence of distractors and attentional factors (Van der Stigchel, 2010; Van der Stigchel, Meeter, & Theeuwes, 2006). However, this study is the first to report the incorporation of such a complex set of high-level cognitive factors: During the eye movement from the center of the screen to the target, spatial aspects of word meanings are integrated with oculomotor programs that are then dynamically adapted over time according to a match vs. mismatch between primes and targets on the semantic level.

The bias in saccade trajectories in the first couple of hundreds of milliseconds after word onset can be interpreted as evidence that semantic processing of up/down words involves direction-specific processes in brain regions that control goal-directed eye movements. One possibility is that oculomotor representations are engaged directly for semantic processing, as part of a situated sensory re-instatement process (Barsalou, 2003; Barsalou, 2009; Barsalou, Simmons, Barbey, & Wilson, 2003). Indeed, accounts of situated conceptualization predict that comprehension of a word (such as *bird*) involves the activation not only of features related to the item itself but also of features related to situations in which it is typically perceived (such as looking up to see the bird somebody is talking about in its nest). Our results that reading up/down words quickly activates direction-specific oculomotor processes and that semantic priming is contingent on the target appearing in its typical location are thus highly compatible with this view. An alternative is that semantic spatial information is retrieved from a high-level spatial system that interfaces with oculomotor regions and activates direction-specific processes therein. Anatomically, this is plausible because systems for covert and overt spatial attention are largely overlapping (Beauchamp, Petit, Ellmore, Ingeholm, & Haxby, 2001; Corbetta et al., 1998; Gitelman et al., 1999; Thompson, Biscoe, & Sato, 2005). As neurons responsible for oculomotor function and covert spatial attention allocation may be intermingled in the same cell populations and are likely to strongly interact (Petersen & Posner, 2012; Schafer & Moore, 2007; Thompson et al., 2005), these two possibilities are very difficult to tease apart. Future studies could investigate to what extent the activation of oculomotor processes by implicitly spatial words is dependent on a secondary task involving eye movements.

Another interpretation of our results is that the modulation of eye movements is the consequence of a location and object matching process (Estes et al., 2015), to the extent that this process directly interacts with oculomotor processes. Under this account the facilitation-to-interference effect for unrelated targets in compatible locations and the strong interference for semantically related targets in incompatible locations can be considered to reflect a clash of the location and object codes. However, it incorrectly predicts the same pattern for geometric shapes that are assumed to be coded as a mismatch for object identity in the same way as unrelated pictures. Moreover, as it stands, facilitation is only predicted for perceptually matching targets, whereas our results suggest that semantically related, but perceptually dissimilar, targets show facilitation in the compatible location. A matching explanation thus could only succeed with the amendment that object codes depend on semantic overlap and that the amount of semantic similarity maps non-linearly onto the outcome: High similarity (semantically related target) produces strong facilitation, no similarity (geometric shapes) produces moderate facilitation, but small degrees of similarity (unrelated pictures that are inanimate object items as the prime words' referents) produce interference. Our results are thus incompatible with the perceptual matching account as initially formulated as the ease of processing of a visual target in compatible location seems to depend on the semantic, not perceptual, relation with the prime word.

Both the location-specific priming effect for semantically related targets and the interference effect for unrelated targets suggest that congruence on one level and incongruence on another is more detrimental than incongruence on both. Previous studies showed that this pattern is only observed at short SOAs (Gozli et al., 2013; Ostarek & Vigliocco, 2017). This is reminiscent of, and can be accounted for, by the theory of event coding according to which sensory-motor features belonging to the same event are temporarily bound into an "event file" (Amer et al., 2017; Hommel, 1998, 2004; Rothermund et al., 2005). As discussed in the Introduction, TEC predicts interference for unrelated targets in compatible locations at short SOAs when spatial features of words are bound and thus unavailable for the visual task, and it predicts facilitation at long SOAs when spatial features are expected to be pre-activated but no longer be bound. Our data, as well as Ostarek and Vigliocco's (2017), suggest that items with partial semantic overlap can be integrated in one event file. An open question is what the boundary conditions are for successful integration, i.e., what kind and amount of features need to overlap for facilitation to occur.

Related to the last point are the somewhat surprising results in the geometric shape condition. Whereas the eye-tracking and RT effects in the semantically related and unrelated conditions pair up nicely, the two measures show a marked difference in the geometric shape condition: The RT data suggest a trend towards interference, but the eye movements show a strong congruency effect. To speculate, it seems possible that the complete lack of feature overlap makes it easier to overcome the inability to integrate the target with the activated event (or event file). This could explain the smaller interference effect in terms of RT and lead to the initial up/down bias in the eye movements to persist.

To conclude, the present study adds to the growing literature on the activation of concepts' typical location in vertical space and, for the first time, shows an interaction of implicit up/down words with direction-specific oculomotor processes during online word processing. Semantic processing of implicitly spatial nouns was found to induce a bias in early stages of concurrently executed saccades that can grow stronger over time or reverse depending on the semantic relation between the prime words and target pictures.

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Figures

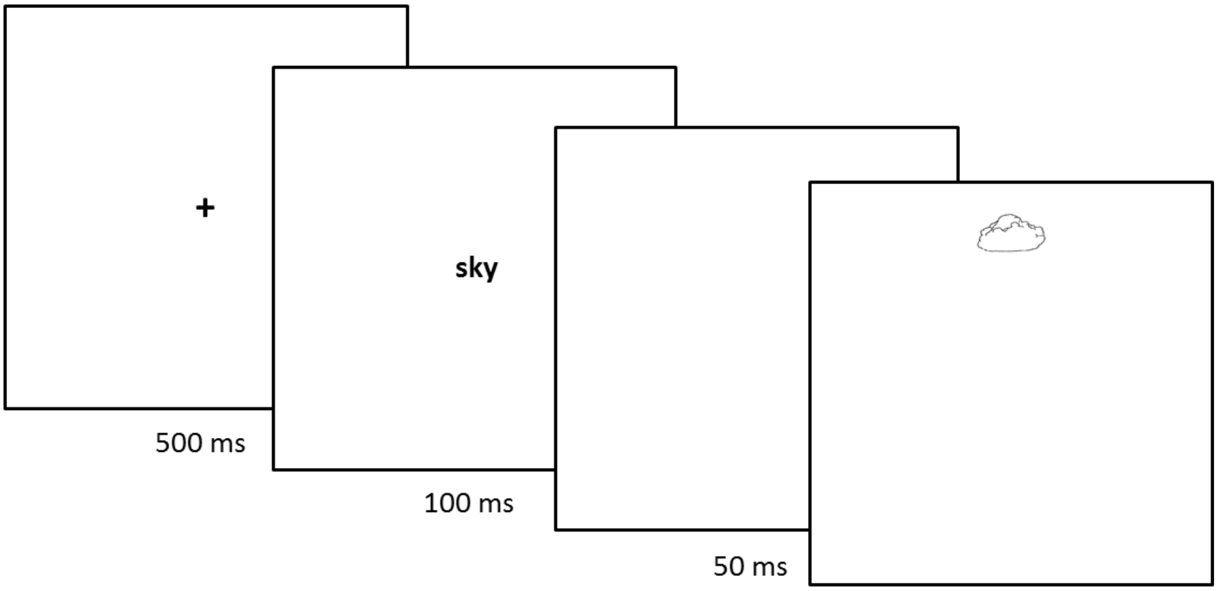

Figure 1: Trial structure illustrated with an up word and a semantically related target in congruent location.

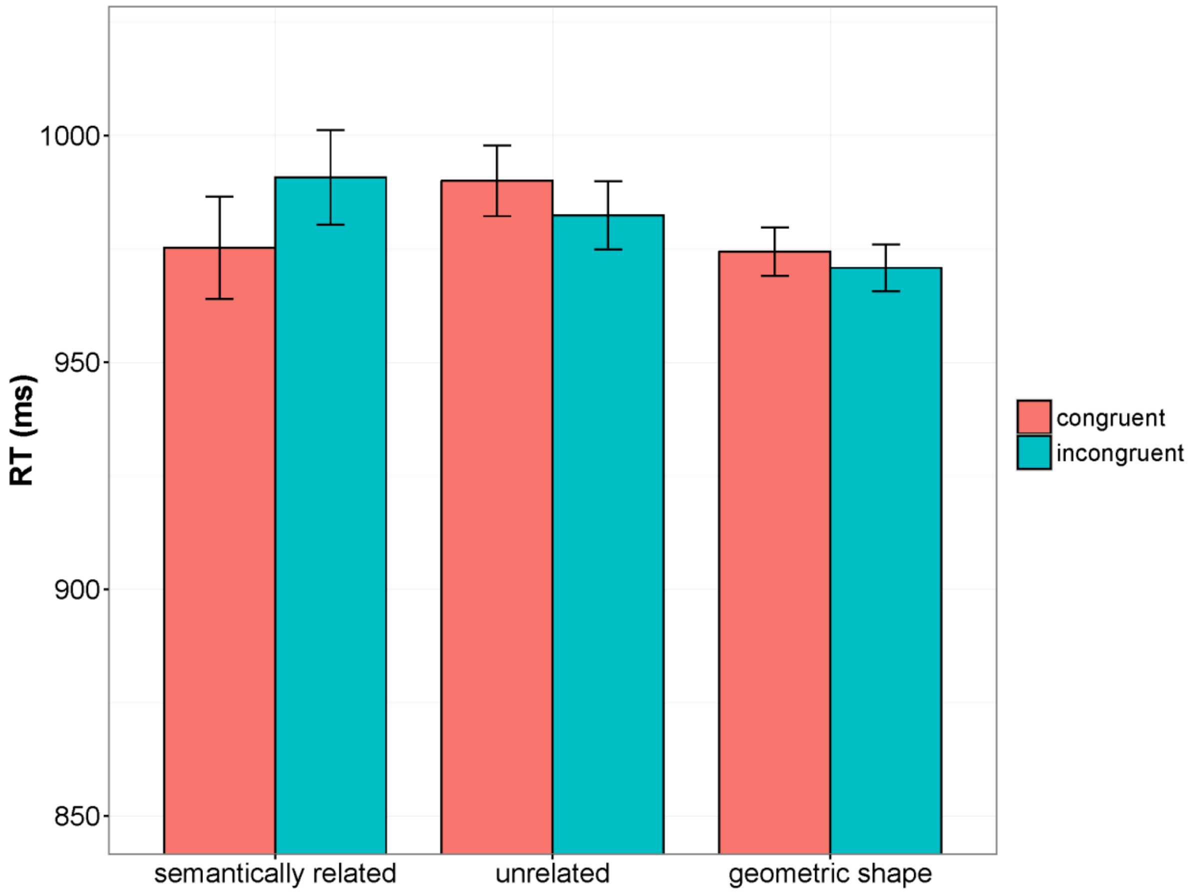

Figure 2: Mean reaction times in all conditions; the x-axis indicates the Prime-Target Relation conditions, Spatial Congruence is color-coded. Error bars indicate 95% confidence intervals.

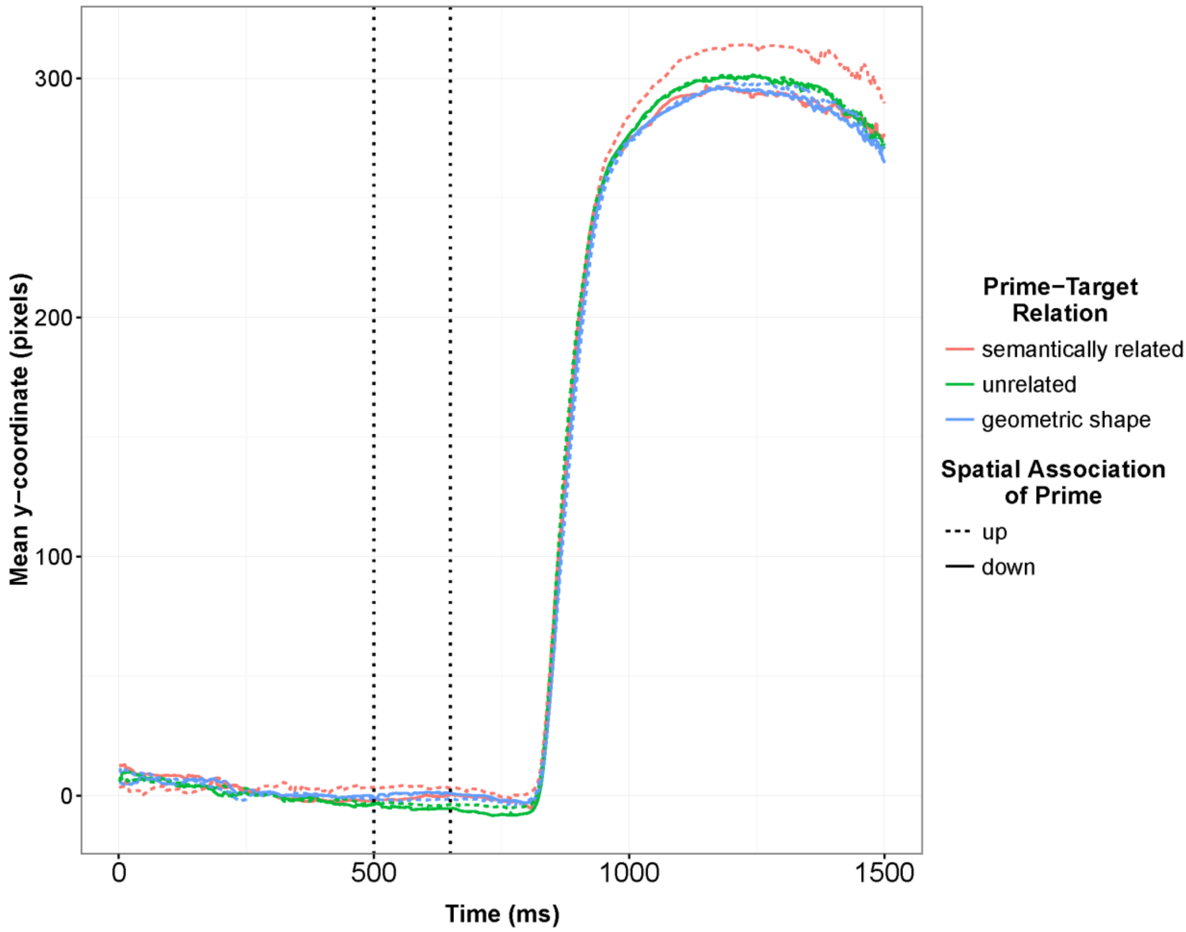

Figure 3: Mean y-coordinates in pixels for up vs. down words at all levels of Prime-Target Relation for all trials with targets at the top of the screen. The vertical dotted lines indicate the appearance of the prime word and the target, respectively.

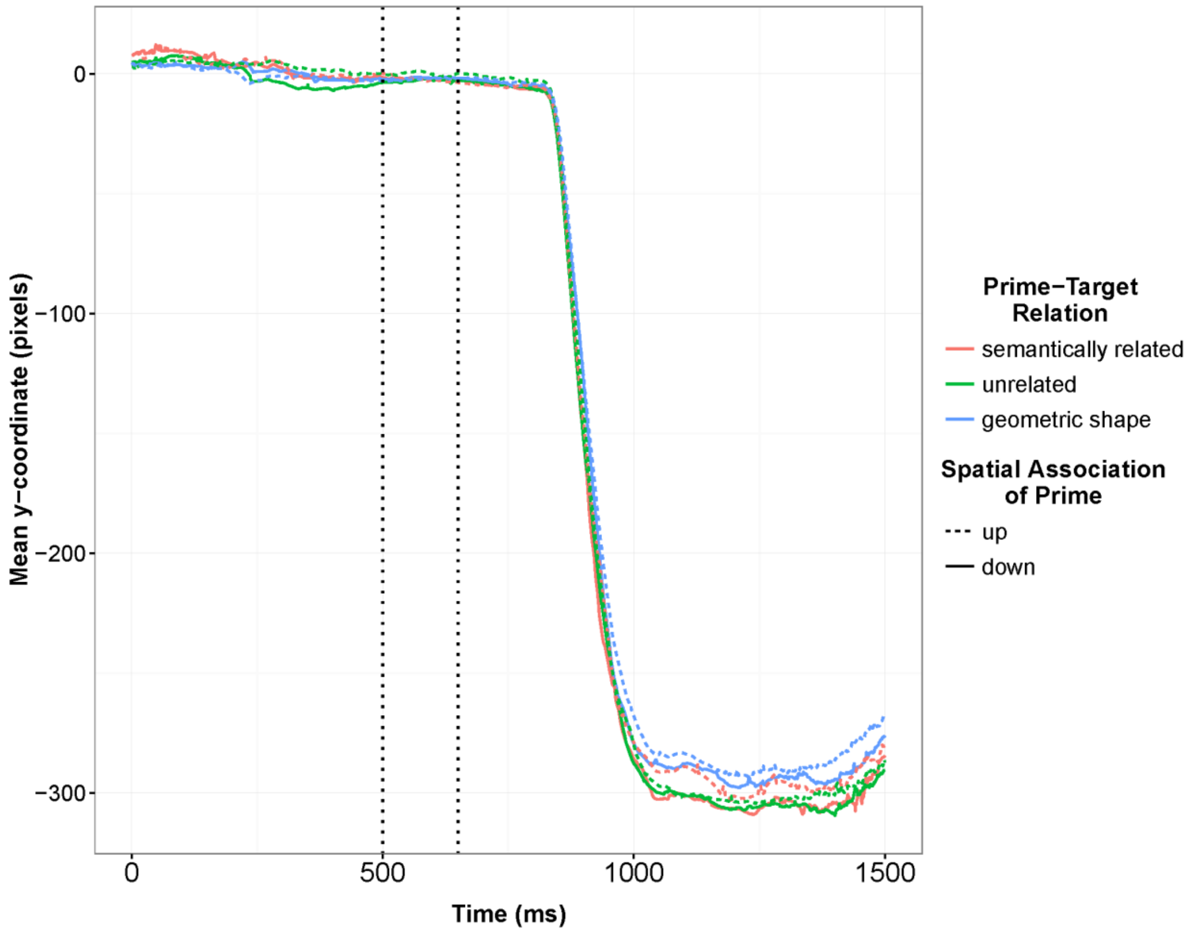

Figure 4: Mean y-coordinates in pixels for up vs. down words at all levels of Prime-Target Relation for all trials with targets at the bottom of the screen. The vertical dotted lines indicate the appearance of the prime word and the target, respectively.

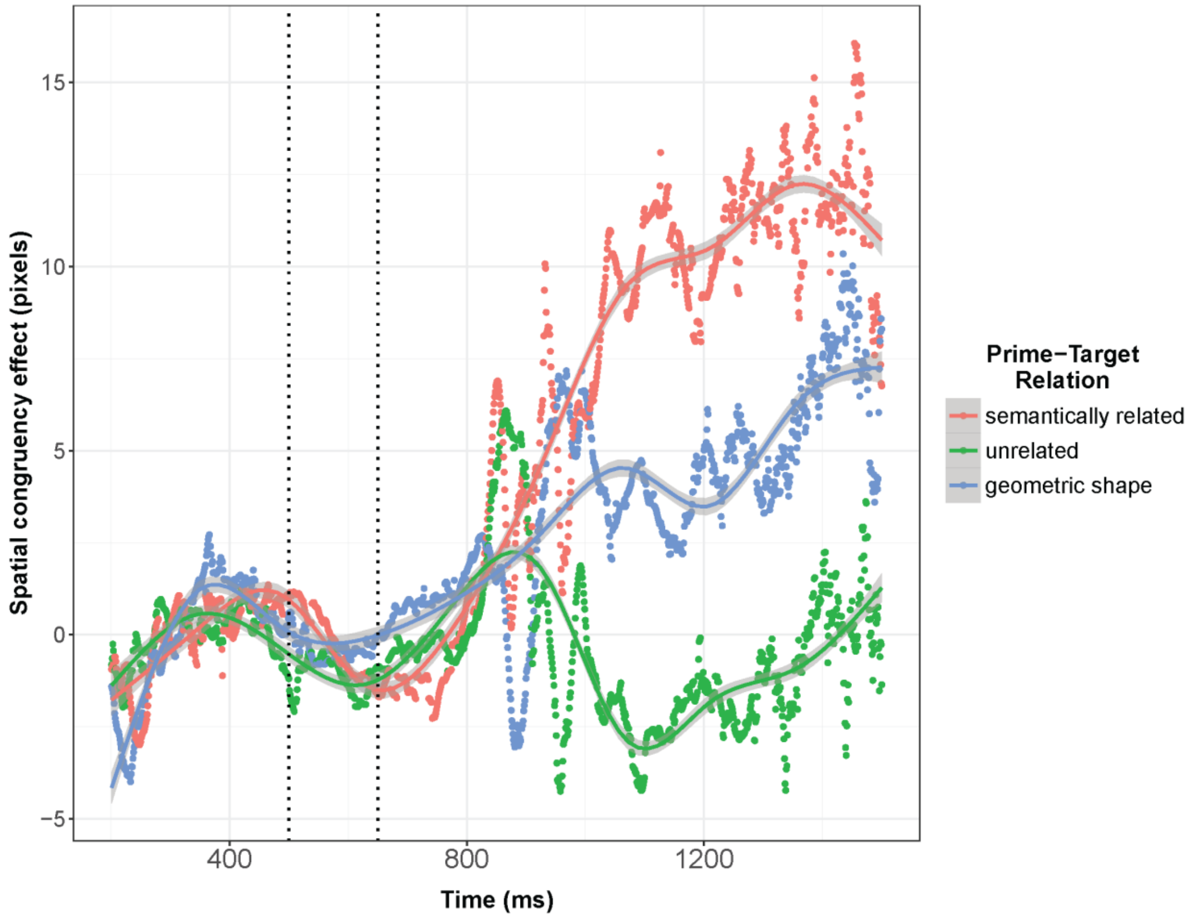

Figure 5: Spatial congruency effect (in pixels) calculated by subtracting normalized mean y-coordinates in down word trials from up word trials for all levels of Prime-Target Association (color-coded) per millisecond. Positive values indicate a bias congruent with the words' spatial associations; negative values indicate a bias in the opposite direction. The vertical dotted lines indicate the appearance of the prime word and the target, respectively.

Appendix

Stimulus characteristics

The table displays means and standard deviations per prime word condition

	Related up	Related down	Unrelated up	Unrelated down	Control
Log-Frequency	2.57 (0.70)	2.35 (0.81)	2.59 (0.63)	2.75 (0.59)	2.61 (0.63)
Age of Acquisition	6.98 (2.52)	6.63 (1.87)	6.7 (2)	6.46 (1.46)	6.17 (1.37)
Syllables	1.79 (0.8)	1.79 (0.7)	1.79 (0.88)	1.64 (0.68)	1.82 (0.77)
Letters	5.86 (2.28)	6.86 (2.71)	6.21 (2.3)	5.57 (1.37)	6 (1.56)
Phonemes	5 (2.15)	6 (2.42)	5.29 (1.94)	4.79 (1.34)	5.25 (1.62)

List of prime words and names of target pictures

Control	Unrelated up	Unrelated down	Related up	Related down	Targets
nagel	adelaar	vloer	hoed	teen	vliegtuig
glas	lamp	octopus	cockpit	muis	engel
telefoon	raam	kakkerlak	zolder	motorfiets	bed
handdoek	vlieg	anker	oog	wortels	fiets
kaars	spreeuw	duikboot	vleugel	vijver	vogel
taart	ooglid	hoeven	kroon	sandaal	pet
schaar	helm	rivier	ster	boot	tapijt
waterkoker	astronaut	kelder	duif	kleedje	wolk
kaas	piek	dolfijn	projectiel	schuilplaats	vlag
horloge	boom	oceaan	pijler	spoor	voet
zwaard	ballon	grot	uil	metro	kikker
meloen	kasteel	slang	hemel	aanhangwagen	gras
wortel	kraag	duiker	regenboog	huifkar	hoofd
envelop	neus	aarde	parachute	kussen	egel
doek	gordijnen	tram			koning
koren	valk	zand			maan
hout	vlinder	stoep			nest
voetbal	satelliet	sok			raket
fles	toren	walvis			dak
cirkel	loopbaan	modder			schip
citroen	bladeren	broek			schoen
tonijn	vlieger	valstrik			zon
rubber	licht	straat			tent
potlood	voorhoofd	steen			trekker
kameel	wolkenkrabber	graf			trein
papier	top	been			tunnel
kokosnoot	planeet	asfalt			paraplu
muur					wiel

English translation of stimuli

Control	Unrelated up	Unrelated down	Related up	Related down	Targets
nail	eagle	floor	hat	toe	airplane
glass	lamp	octopus	cockpit	mouse	angel
telephone	window	cockroach	attic	motorbike	bed
towel	fly	anchor	eye	roots	bicycle
candle	starling	submarine	wing	pond	bird
cake	lid	hooves	crown	sandal	cap
scissors	helmet	river	star	boat	carpet
kettle	astronaut	cellar	pigeon	rug	cloud
cheese	peak	dolphin	missile	shelter	flag
watch	tree	ocean	pillar	rail	foot
sword	balloon	cave	owl	metro	frog
melon	castle	snake	sky	trailer	grass
carrot	collar	diver	rainbow	carriage	head
envelope	nose	earth	parachute	pillow	hedgehog
cloth	curtains	tram			king
corn	falcon	sand			moon
wood	butterfly	pavement			nest
football	satellite	sock			rocket
bottle	tower	wale			roof
circle	orbit	mud			ship
lemon	leaves	pants			shoe
tuna	kite	snare			sun
rubber	light	street			tent
pencil	forehead	stone			tractor
camel	skyscraper	grave			train
paper	summit	leg			tunnel
coconut	planet	asphalt			umbrella
wall					wheel