

*On the screen, in the mind:*  
An ERP investigation into the interaction  
between visuospatial information and spatial  
language during on-line processing

by

Emily Zane

A dissertation submitted to the Graduate Faculty in Linguistics in partial  
fulfillment of the requirements for the degree of Doctor of Philosophy, The City  
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This manuscript has been read and accepted for the  
Graduate Faculty in Linguistics to satisfy the dissertation  
requirement for the Doctor of Philosophy.

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# Abstract

This project used Event-Related Potentials (ERPs) to explore neurophysiological brain responses to prepositional phrases involving concrete and abstract reference nouns (e.g., "plate" and "moment", respectively) after the presentation of photographs of objects with varying spatial features. Phrases were either matching (e.g., "in the plate/moment") or mismatching ("on the plate/moment"). Conjunction phrase matches and fillers were also presented. Before half of the concrete-phrase items, a photographic depiction of the reference noun was presented. In these photographs, objects were displayed in a way that was either more appropriate for *in* or for *on*. Similarly, before half of the abstract-phrase trials, photographs of nonce objects with spatial features that were either more appropriate for *in* or for *on* were presented. For the remaining trials, either no picture was displayed or a picture of a random object was displayed.

Results indicated that linguistic and visual context impacted ERPs to words in these phrases. Beginning with linguistic context, all prepositional phrases yielded negative slow-wave activity in parietal and occipital sites, while conjunction phrases did not. Because this negativity is modulated by processes involved in the generation and manipulation of spatial imagery, this finding indicates that a similar spatial-image-formation process is involved in the processing of both concrete and abstract prepositional phrases. There were differences between responses to concrete and abstract phrases as well. Mismatching concrete reference nouns yielded a relatively large centro-parietal N400 response, suggesting that these nouns were semantically unexpected. Mismatching abstract nouns, on the other hand, yielded a late, marginally significant positivity, showing that the presentation of these nouns required phrase reanalysis and/or reconstruction. The latter result casts doubt on accounts of polysemy claiming that abstract uses of prepositions are cognitively and metaphorically linked to their spatial senses.

Visual stimuli also impacted responses to the phrases. The type of object presented in the picture before the phrase impacted N400 responses to prepositions, where pictures of *in* objects yielded smaller N400 responses to *in* and vice versa for *on*, no matter the configuration of the object in the picture. This suggests that an object's category – rather than its specific visual in a particular context– primes a preposition's lexical denotation. The impact of object type was also observable downstream from the N400 to prepositions. Parieto-occipital slow-wave negativity increased after the presentation of random objects and after the presentation of no picture as compared to responses to phrases presented after pictures of *in* or *on* objects. This result implies increased reliance on internal image-formation processes to scaffold linguistic processing when external visual information does not facilitate phrasal interpretation and/or recollection.

While the spatial configuration of the object presented in the picture before the phrase did not impact responses to prepositions, it did impact responses to concrete reference nouns. Pictures of objects in spatially mismatching configurations elicited frontal N400 effects, which are believed to index the amodal incorporation of image-mediated information into on-line semantic processing. Frontal N400s were also impacted by phrase type (match versus mismatch), where frontal N400s to matching nouns after spatially mismatching pictures dissipated earlier than for mismatching nouns, suggesting that processes involved in integrating visual context are completed more quickly (and perhaps less effortfully) when the noun is primed by semantic context than when it is not. This is similar to the response pattern for prepositions – when prepositions were unprimed by semantic (visual) context, there was increased effort involved in spatial-image formation.

Together, results reveal a multifaceted interaction between phrasal expectations and visual priming during the processing of natural spatial language about real-world objects and abstract concepts. More broadly, findings imply that the processing of all language, even simple phrases containing words that are believed to have limited semantic content, engages a complex neural network involving linguistic and non-linguistic representations.

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# Chapter 1

## The language of space

*Spatial prepositions are difficult to define because they do not link to real-world, perceptible referents, and instead refer to generalized, perhaps schematic representations of relationships between perceptible referents. This chapter describes different methods for defining prepositions, including spatial prototypes and image schemas, and then connects these definitions to discoveries from behavioral and neurophysiological research into visuo-spatial and spatial-language processing.*

## 1.1 Geometry in language

Language can be used to successfully describe spatial information in the world, so that a person can use language to locate objects, to be directed to a location, and to orient herself to her surroundings. However, the relationship between linguistic forms and spatial configurations is not iconic, nor is there a one-to-one correspondence between spatial configurations and linguistic forms.

The following example illustrates this. Figure 1.1 presents an arrangement between a triangle and some circles:

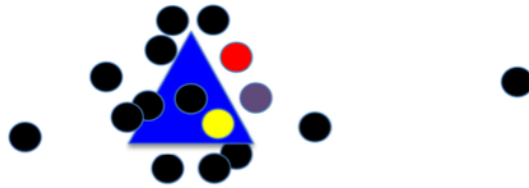


Figure 1.1: Circles and triangle

In this figure, several circles appear in various spatial configurations in relation to a blue triangle. When an x- and y-axis are overlaid on this image so that the zero-point for the axes is the midpoint of the triangle, each circle's position is uniquely describable (see Figure 1.2). The red circle is positioned outside of the triangle's boundaries, about 5 millimeters from the triangle's midpoint and 45-degrees above the triangle's x-axis. The purple circle is outside of the triangle's boundaries, about 5 millimeters from its midpoint on its x-axis.

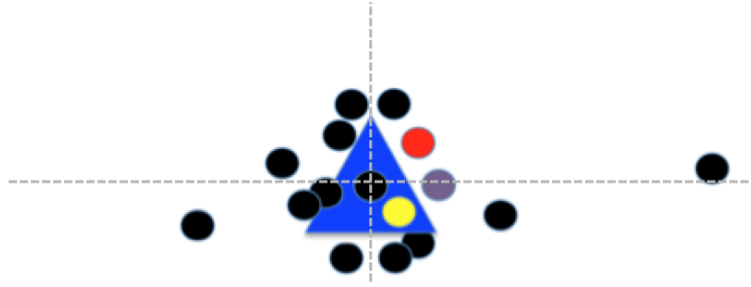


Figure 1.2: Circles and triangle

Theoretically, language could have a unique term for each of these configurations, e.g., *the red circle floops the triangle*, where *floop* denotes that the first object is positioned 5 millimeters from the midpoint of another object and 45-degrees above the object's x-axis. In this way, language would utilize an expansive set of terms to describe an expansive (infinite) set of spatial possibilities.

But language does not do this; instead, it uses a small set of forms to represent spatial scenes. In English, for example, prepositions like *in*, *on*, *above* and *below*, are used.

For example, the yellow circle (in Figures 1.1 and 1.2) would probably be described as being *in* the triangle and the red and purple circles would both probably be described as being near or next to the triangle, even though their positions are obviously distinct from each other.

The linguistic elements that are used to describe spatial scenes in languages are typically adpositions (e.g., *in*) or verbal affixes (e.g., *inset*). These elements be-

long to closed-class sets; the term "closed-class" signifies that the set contains few items and infrequently admits new members. This is in contrast to "open-class" categories, like nouns and verbs, which contain relatively many items and are constantly being expanded. A comparison between these sets is striking: there are only about 80-100 prepositions in the entire English language, while the average English speaker uses roughly 10,000 count nouns (Landau and Jackendoff 1993, Coventry and Garrod 2004). Because there are comparatively few terms for spatial relationships, and because there are infinitely possible spatial configurations between objects in the world, it follows that the spatial denotations of each spatial word must be at once vague, underspecified and vast. Further, the fact that a finite set of closed-class items is used to describe spatial relationships suggests that spatial terminology is a fundamental and ontological category in language (Talmy 1983, Regier 1996). Furthermore, if linguistic categories are thought to represent perceptual and conceptual experience, it follows that members of this finite set of spatial terms map to fundamental units of spatial perception and conception (Grady 2005, Mandler 2010).

### 1.1.1 Terminology

A spatial preposition often establishes a relationship between two objects. For example, in the sentence *the circle is in the triangle*, *the triangle* is used as the reference object to which *the circle*, a located object, is oriented. The reference and located objects have numerous designations in the literature, including: "sec-

ondary" and "primary" object by Talmy (1983), "landmark" and "trajector" by Lakoff (1990), "ground" and "figure" by Langacker (2009), "reference entity" and "located entity" by Herskovitz (1986), and "reference" and "located object" by Coventry and Garrod (2004), respectively. In this paper, these two objects are referred to as reference and located objects, as these avoid the visual connotations of figure and ground and the sense of movement implied by trajector and landmark (See similar arguments in Coventry and Garrod (2004), Herskovitz (1986)).

There is typically an asymmetry between reference and located objects, where reference objects are relatively larger, less movable, and/or more salient than located objects; the reference object is also often the one that has occurred earlier, either in the spatial scene being described or in discourse or memory (Talmy 1983). For instance, if a speaker were to describe the position of the red circle in Figure 1.1, she probably would not locate its position with regards to the other circles without mentioning the triangle, e.g. *the red circle is between a black circle and the purple circle*. Nor would she locate the triangle in regards to the red circle, e.g., *the blue triangle is near the red circle*. Instead, she would most likely pick out the triangle as the largest and most salient object, and therefore use it as the reference object to which the circle's position is identified (e.g. *the red circle is near the blue triangle*).

There is an abundant body of work that has labored to establish geometric denotations for spatial terms in English (Cooper 1968, Miller and Johnson-Laird 1976, Talmy 1983, Herskovitz 1986, Landau and Jackendoff 1993). For exam-



ple, in the following diagram, Figure 1.3, each of the yellow circles occupies a unique position; however, all of the circles can be described as being *in* the blue triangle.



Figure 1.3: Circles and triangle

Based on this type of example, the denotation of the preposition *in* has been described as establishing a relationship between objects, whereby a located object is internal to (the boundaries of) a reference object (Bennett 1968, Cooper 1968, Leech 1970, Herskovitz 1986), see Table 1.1 for terminology.

When applied to other configurations, this definition accurately predicts when *in* can be applied and when it cannot. For instance, the yellow circles in Figure 1.4, below, are *in* the triangle, while the black circles are not.



Figure 1.4: Circles and triangle

## Geometric denotations for the preposition *in*

Author	Function	Definition
Cooper (1968)	$x \text{ in } y$	$x$ is located internal to $y$ , with the constraint that $x$ is smaller than $y$
Leech (1970)	$x \text{ in } y$	$x$ is 'contained' or 'enclosed' either in a two-dimensional or in a three-dimensional place $y$
Bennett (1968)	$\text{in } y$	Locative(interior( $y$ ))
Miller and Johnson-Laird (1976)	$\text{in}(x,y)$	A referent $x$ is <i>in</i> a relatum $y$ if: [PART ( $x, z$ ) and INCL ( $z, y$ )]
Herskovitz (1986)	$\text{in } (x, y)$	Inclusion of a geometric construct of $x$ in a one-, two-, or three-dimensional geometric construct of $y$

Table 1.1: Definitions for *in* (Adapted from Garrod et al. (1999)).

### 1.1.2 Testing the relationship between preposition use/understanding and geometry

Geometric denotations for prepositions are supported by empirical research. For instance, when participants are asked to designate the position *in* a reference object, participants are remarkably consistent: They identify an area within the object's boundaries (Hayward and Tarr 1995, Logan and Sadler 1996). See Figure 1.5.

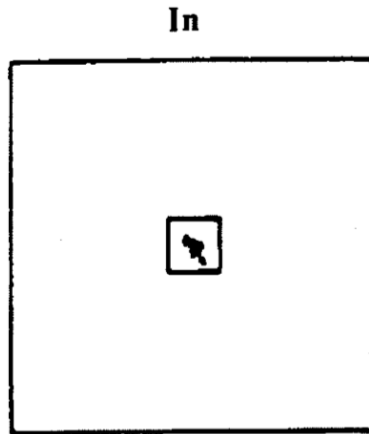
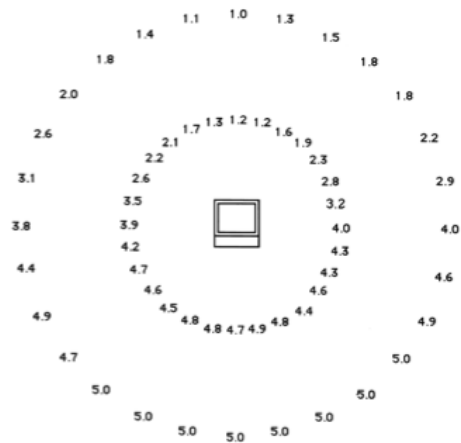
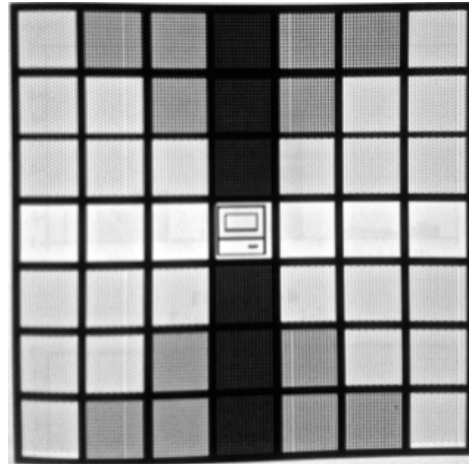


Figure 1.5: Participants' *in* designations, from Logan and Sadler (1996)

Likewise, when participants are asked to rate uses of prepositions to describe scenes, geometric factors, like direction and orientation, affect their rating scores (Hayward and Tarr 1995, Logan and Sadler 1996, Crawford et al. 2000). See Figure 1.6.



(a) Mean ratings for the use of *above* to describe different positions relative to a reference object. Lower scores indicate higher acceptability ratings. (Crawford et al. 2000)



(b) Mean acceptability ratings for *above* and *below* used for different positions relative to the reference object. Darker squares indicate higher acceptability ratings from Hayward and Tarr (1995), adapted by Garrod et al. (1999)

Figure 1.6: Results from Crawford et al. (2000) and Hayward and Tarr (1995)

Geometric definitions of prepositions also make predictions about the features of reference and located objects that will be used with a particular preposition. As explained in Section 1.1.1, the geometry of the reference object is generally more constrained than that of the located object for a preposition (Talmy 1983). For instance, the definitions for *in* presented in Table 1.1 all predict that a reference object in an *in* relation must be one that is conceivable as having interior space. There is no real constraint on the located object in these definitions, except for Cooper (1968), where the located object is predicted to be smaller than the reference object.

These predictions have been affirmed by behavioral research. Michele Feist and Dedre Gentner found that varying the concavity of a depicted reference object affects the proportion of times a participant uses *in* or *on* to describe a scene involving that object (1998, 2011). See Figure 1.7, below.

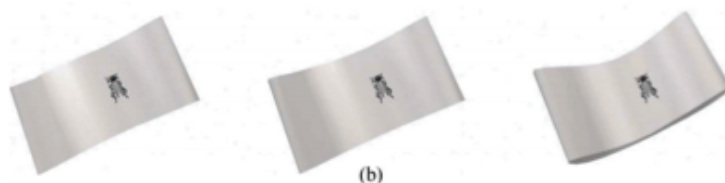


Figure 1.7: Reference objects at three concavity levels: low (flat), medium, and high from Feist and Gentner (2011)

As the level of concavity of the reference object increases, so do uses of *in*; the inverse effect is found between levels of concavity and uses of *on* (1998, 2011). The authors' conclusion is that higher levels of concavity result in an increased conception of a reference object as having interior space. And, when the reference object is conceived as having an interior, this increases the likelihood that located objects can be *in* it.

## 1.2 Spatial prototypes

The behavioral results presented above not only suggest that certain spatial regions are conceived as more or less appropriate for a given spatial label, but that there is a systematic (and even linear) relationship between geometry and spatial language

use/acceptability, where the further a point is from a particular geometric location, the less acceptable a preposition is.

Consider, for example, the results of Crawford et al. (2000) (see Figure 1.6a): The most acceptable *above* region (corresponding to a mean acceptability score of 1.0) is a position both higher than the reference object and directly on the reference object's y-axis. As the points angle away from this position (in both directions from the vertical axis), acceptability ratings systematically drop, so that the lowest ratings are those approximately 180 degrees from this point.

The same can be said for the results of Feist and Gentner (1998, 2011), where there is a linear relationship between concavity levels and ratings of *in*. Again, there seem to be varying degrees to which a scene represents *inness*. Certain scenes (those with a more concave reference object) are good exemplars of *in*; as concavity decreases, ratings for *in* get worse, as though there is a scalar (versus binary) appraisal of a preposition's fit for a given scene. In short, it seems that certain configurations are in accordance with a mental prototype for a preposition; as configurations shift away from this prototype, the preposition becomes a less and less acceptable label.

These effects have been shown to influence participants' memories of a visual scene (Feist and Gentner 2001). When participants are shown a picture of two objects in a borderline *on*-configuration (Figure 1.8, left), they falsely recall having seen a more prototypical *on*-configuration (Figure 1.8, middle) much more frequently than they do a scene to which *on* cannot apply (Figure 1.8, right).

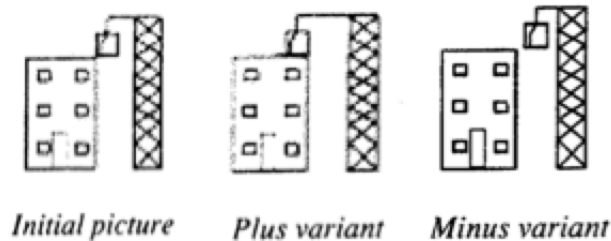


Figure 1.8: Materials from Feist and Gentner (2001): Left: Initial picture of an atypical *on* scene; Middle: More typical *on* scene; Right: Not *on* scene

Interestingly, this effect *only* occurs in cases in which participants read a linguistic description of the scene while looking at the picture, i.e., *the picture shows a block on a building*. No such effect occurs in the cases when participants do not receive a verbal description of the scene. Nor does it occur when participants read a control, non-spatial description of the scene, i.e., *the picture shows a block and a building*. These patterns persist even when participants are strongly encouraged to remember the scene, which perhaps encourages linguistic encoding in cases when no overt linguistic information is provided. These results suggest that a preposition is associated with a prototypical spatial scene. The effects of this prototype are so influential that they may interfere with memories of actual perceived visual information

These sorts of effects have also been revealed in young children, between the ages of 15 and 24 months (Meints et al. 2002). In a looking-time experiment, children were shown pairs of pictures of located and reference objects in prototypical and less typical spatial relationships for the prepositions *on* and *under*. It was discov-

ered that 15-month-olds only associate *on* and *under* with a prototypical spatial array, where located objects are on or near a vertical axis that bisects the reference object's center of mass. This is similar to the adults' designations of *above* and *below* from Logan and Sadler (1996).

Older children, 18- and 24-month-olds, have expanded their denotations of *on* and *under* to include less typical arrangements. However, the looking-time patterns for these children still reveal prototype effects: They look longer at atypical scenes than they do typical ones. Taken together, these results suggest that prototypical or central senses of *on* and *under* are acquired very early (by or before 15 months). Once the scope of their meanings is broadened (by 18 to 24 months), some representation of the prototype remains, so that children with a broader definition of these prepositions are aware that a spatial scene is atypical and consequently spend a longer time inspecting it.

The above-described studies provide evidence that each preposition is associated with a prototypical spatial configuration, so that a particular type of configuration is considered a best or most typical exemplar of the preposition's meaning, and so that each instantiation of prepositional use is a transference to or extension from this prototypical sense.



### 1.3 Image schemas

Based on prototype effects, several authors have argued that the determination of the level of a preposition's acceptability or appropriateness for describing a particular scene depends on comparing the spatial configuration depicted in that scene to a mental representation of a preposition's prototypical spatial arrangement, a so-called "spatial template" or "image schema"; the less a visuo-spatial scene aligns with a preposition's associated spatial image, the less acceptable that preposition will be for describing the scene (Hayward and Tarr 1995, Regier 1996, Logan and Sadler 1996, Carlson-Radvansky and Radvansky 1996, Mandler 2010).

Models of image schemas and spatial templates depart from describing prepositional meaning in propositional formulae (like those in Table 1.1). Instead, image schemas describe a preposition's meaning using models of spatial imagery. These models attempt to directly connect word meaning to perceptual experience (Lakoff 1990).

There is an on-going debate about what image schemas are and how they are mentally represented (Grady 2005, Mandler 2010). Visual images are mental representations of scenes perceived visually; auditory images are mental representations of scenes perceived auditorily, *et cetera* (Kosslyn et al. 2001). *Spatial* information, on the other hand, is not sensory; there is no direct spatial sensory perception (except, perhaps, when reading maps<sup>1</sup>). Since spatial knowledge and representation

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<sup>1</sup>See Tversky (2011), for a discussion of maps and diagrams as visual manifestations of spatial

is always an abstraction, and since spatial imagery is based on conception instead of *perception*, it is likely that spatial images (if they exist) are not mental pictures, but instead are abstract mental models of spatial relations. Whether these images are constructed from built-in primitives, or abstracted and acquired from perceptual experience is up for debate (Mandler 2010).

In order to explicate how image schemas are depicted and how they work to represent prepositional meaning, the following example from Brugman and Lakoff (1988) and Lakoff (1990) is provided. Below, is an image schema for the preposition *over*:

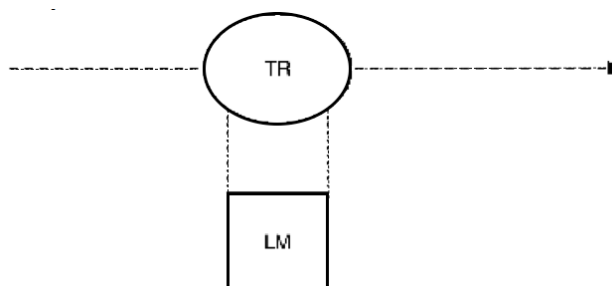


Figure 1.9: Schema 1 for *over* from Brugman and Lakoff (1988), Lakoff (1990). "TR"= Located object; "LM"= Reference object

According to Brugman and Lakoff (1988) and Lakoff (1990), each preposition is associated with a central sense, which corresponds to a core, prototypical image schema, or an "idealized conceptual model". Figure 1.9 is a representation of *over*'s central sense. *Over* is used for all sorts of different spatial and non-spatial concepts/cognition and the possibility of a bidirectional priming relationship between maps and spatial cognition.



## 1.4 Image schemas and spatial prototypes in neural networks

Theoretical models of image schemas have led to computational neural networks of visual-spatial and spatial-language processing and acquisition. These models test how well image schemas and prototype effects can account for preposition acquisition and use.

A spatial neural network is constructed by connecting spatial templates to their associated prepositions, along with algorithms that allow the network to evaluate how well different visual (and sometimes multimodal) scenes align with the template for a given preposition. When this network is then presented with pictures or videos of spatial configurations, it can successfully identify the level to which a preposition matches the scene (Lockwood et al. 2005, 2006, Lockwood 2009, Lipinski et al. 2012).

Interestingly, Regier (1996) discovered prototype effects after created a program with a model for spatial language acquisition. He did not explicitly identify certain scenes as more typical than others. However, as he trained the network to recognize which scenes depicted a preposition, the computer began to recognize that certain scenes were more common than others. The program consequently treated more common scenes as prototypes, or as "better" examples of a preposition, and graded other scenes in comparison to that prototype (p. 145-152). Regier con-

cluded that prototype effects are a *consequence* of perceptual experience, rather than built into sensory mechanisms.

## 1.5 Neurophysiology and spatial language

### 1.5.1 Spatial language processing and spatial image formation

Neurophysiological research supports the involvement of mental imagery or templates during the interpretation of spatial language and during the application of spatial language to visual scenes.

In general, neurological research has found that specialized brain areas are recruited during the processing of language that encodes spatial information and relationships. These brain regions differ from those recruited to process concrete nouns, action verbs, and non-locative thematic relations. The areas that are activated during the processing of spatial language and information include the left angular gyrus, the left supramarginal gyrus, and left posterior and inferior parietal regions (Carpenter et al. 1999, Damasio et al. 2001, Tranel and Kemmerer 2004, Wallentin et al. 2005, Emmorey et al. 2005, Kemmerer 2006, Noordzij et al. 2008, Chatterjee 2008, 2010).

Electrophysiological research supports this as well. Noordzij et al., for example, discovered that a parieto-occipital negativity, beginning about 550ms post stimulus onset, is evoked by spatial phrases (e.g. *the circle left of the triangle*), but

not by similar, non-spatial phrases (e.g. *the circle and the triangle*) (2006; See Figure 1.11). Because the amplitude of the parieto-occipital slow-wave elicited by spatial language increased when participants expected to see a picture after the sentence, and because parieto-occipital negativity has been associated with increased effort in the generation and manipulation of mental imagery in previous research (Bosch et al. 2001, Tadi et al. 2009, Lopez et al. 2011), Noordzij et al. (2006) conclude that the parieto-occipital negativity indexes the involvement of mental imagery (i.e., image schemas) during spatial language processing.

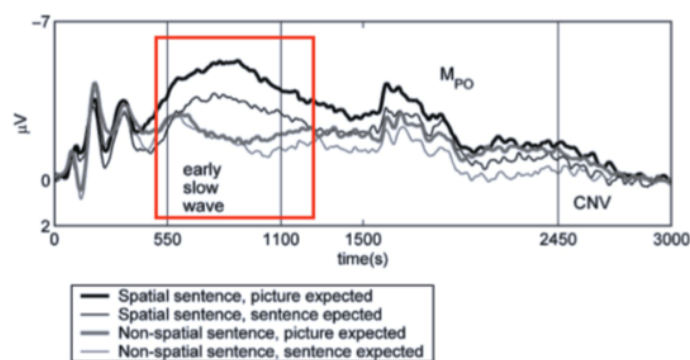


Figure 1.11: Comparison of parieto-occipital negativity from Noordzij et al. (2006). The relevant time-window is in the red box (added), from about 550ms-1250ms post-stimulus onset.

There is some evidence that the processing of spatial terms used to convey abstract or temporal information, for example "I am at my wit's end" and "I will meet you at 10:00", is neurally distinctive from the processing of these terms used spatially, for example "I will meet you at the store" (Kemmerer 2005, Wallentin et al. 2005). This result has also been replicated in the behavioral findings of Bergen et al. (2007), who discovered interference effects between the processing of spatial lan-

guage –movement verbs in sentential contexts, for example, "the mule climbed"– and visual information. When real visual information was displayed to participants in the portion of the screen (the top or the bottom) that matched the directional information encoded by the verb, participants were slower to recognize the object. The same effect was not observed when these same verbs were used in metaphorical ways, as in "the cost climbed". This suggests that the brain regions involved in semantically decoding a spatial sentence are not implemented when particular words are used, but only when these words are used spatially.

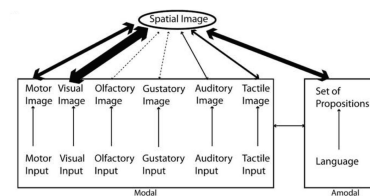
The regions activated during spatial language processing overlap those recruited for non-linguistic spatial imagery tasks, like mental navigation through space, mental rotation of an object, and mental distance comparison (Carpenter et al. 1999, Mellet et al. 2000, Creem and Proffitt 2001, Mazoyer et al. 2002, Formisano et al. 2002, Trojano et al. 2006). This overlap suggests that the processes involved in mental image formation and manipulation are at least partially implicated in the interpretation of spatial language. For example, the left supramarginal gyrus has been found to be active during the production and maintenance of spatial images, no matter the context in which they were generated, i.e. after verbal or visual instructions and input (Noordzij et al. 2008). This suggests that the mechanisms involved in generating and manipulating spatial images are independent of verbal and visual processing, so that the neurological process of spatial-image building is identical whether external input is linguistic or visual (Struiksma et al. 2009).

Evidence indicates that the mechanisms involved in creating, updating and analyzing spatial imagery and language are largely separable from those involved in visual encoding of information. This supports the theory that spatial images are not simply visual, but are instead are abstractions derived from a variety of sensory experiences of spatial relationships. The regions of the brain recruited for spatial language and visuo-spatial image processing only partially overlap with those recruited for general visual image tasks and visual perception (West and Holcomb 2000, Kosslyn et al. 2001, Kemmerer 2006, Kaski 2002). Additionally, the same parietal regions are activated when spatial input is visual and when it is haptic, which suggests that these regions are involved in processing spatial information, no matter the sensory modality of the input (Wolbers et al. 2011). And finally, the same regions recruited during spatial mental processing and spatial language processing in sighted individuals have been found to be activated in *blind* individuals, which suggests that the mechanisms involved in generating spatial images are hard-wired and do not rely on direct visual experience (Bértolo 2005, Struiksma et al. 2009, 2011).

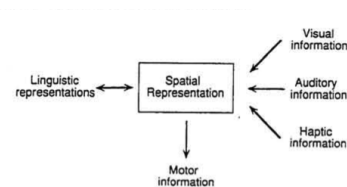
Taken together, these facts have led to a hypothesized organization of spatial representation and perceptual/linguistic input where spatial representation is independent of input modality. Language and sensory processes feed the same representation (Wolbers et al. 2011). This spatial representation is either supramodal (Barsalou 1999b,a, Cattaneo and Vecchi 2008, Struiksma et al. 2009) or amodal (Friederici and Levelt 1990, Landau and Jackendoff 1993, Bryant 1997) organization of spatial imagery, whereby verbal information and sensory perception work



to feed a common spatial representation.



(a) Supramodal organization from Struiksma et al. (2009)



(b) Amodal organization from Landau and Jackendoff (1993)

Figure 1.12: Supramodal and amodal organizations of spatial imagery. In 1.12a, the level of contribution of these modalities is variable, as indicated by the varying thickness of arrows.

A crucial difference between the proposed amodal and supramodal organizations is that supramodal organization includes bi-directional connections between perception and spatial representation, while amodal organization only allows feed-forward connections from sensory perception to spatial representation. The former assumes traces of input modality will remain activated when a spatial image is constructed, while the latter does not.

Struiksma et al. (2009) argue that the neurobehavioral evidence better supports a supramodal organization, since there is neural evidence that modality-specific regions are activated along with regions associated with spatial imagery during tasks that require recollection of spatial information. Cattaneo and Vecchi (2008, 2011) make a similar argument for supramodal organization of spatial representation and spatial memory, based on the results of neurological and behavioral experiments with sighted and blind participants; though Cattaneo and Vecchi (2011) point out

that the terms "supramodal", "amodal" and "multimodal" are often confused in the literature (especially the first two) and are sometimes used interchangeably.

In summary, neurophysiological evidence shows that both spatial language and other types of spatial input activate inferior parietal regions that are involved in other spatial imagery tasks. This suggests that there is a single, supramodal or amodal neural mechanism that models spatial information (Bryant 1997, Noordzij et al. 2008).

### **1.5.2 The *what* and *where* stream**

Many authors argue that parietal activation during spatial tasks (processing spatial language and imagining spatial scenes) is explained by the separation of two neural processing axes or streams, the ventral and dorsal pathways, or "what" and "where" streams, respectively (Landau and Jackendoff 1993, Wu et al. 2008).

The "dual-stream hypothesis" is a proposed method by which primates process visual information. According to this hypothesis, during the visual processing of objects, two functionally independent neural pathways, a ventral stream and a dorsal stream, connect areas of the primary visual cortex in the occipital lobe to the temporal and parietal lobes. The ventral "where" stream, which connects the primary visual cortex (V1) to the temporal lobe, is activated during the visual processing of objects; the dorsal stream, which connects V1 to the parietal lobe, is activated during the visual processing of spatial information (Ungerleider et al.

1983, Mishkin et al. 1983, McIntosh and Schenk 2009). Neurons in the "what" system are activated by visual tasks that require matching patterns to one another and in the visual recognition of detailed features of objects (i.e., shape, color, size, etc.), whereas neurons in the "where" system are activated by object localization tasks and spatial matching tasks (Haxby et al. 1994).

These streams are also involved in the processing of information that is not directly perceived. The ventral and dorsal systems are each independently implemented in imagery tasks- in imagining object shape or object location (Levine et al. 1985, Kosslyn et al. 2001, Mazoyer et al. 2002, Just et al. 2001). Separate dorsal and ventral activation has also been observed in subjects with impaired perception and in congenitally blind subjects (Kosslyn et al. 2001, Struiksma et al. 2009). And finally, there is evidence that linguistic tasks involve these streams: damage to the dorsal stream affects the use and comprehension of spatial terms (e.g., prepositions), while damage to the ventral stream affects the use and comprehension of terms for other object relationships (Chatterjee 2008, 2010).

Landau and Jackendoff (1993) propose that distinctions between the dorsal and ventral system directly correlate with disparities between object language and spatial language. As discussed in Chapter 1, the language used to label objects is rich and complex, while the language used to label spatial relations is limited and schematic. Similarly, the ventral "what" system is sensitive to detailed information about object shape, color, etc., and the dorsal "where" system is not. Dorsal neurons are instead only sensitive to object position and whatever rough repre-

sentation of object shape is necessary to determine this. Landau and Jackendoff therefore claim that the asymmetry between object and spatial language are due to a neural asymmetry between object and spatial perception (1993).

## Chapter 2

### Beyond geometry

*Prepositions are often used to describe the spatial relationships between real-world, three-dimensional objects. The features of these objects impact what prepositions will be selected to describe spatial relationships involving these objects. This chapter reviews behavioral and neurophysiological research which examines how features of three-dimensional real-world objects impact the way prepositions are used and interpreted.*

## 2.1 Spatial language describing three-dimensional, real-world objects

A shortcoming of much of the neurophysiological research discussed in Section 1.5 is its limited use of linguistic and visual materials. Many paradigms involve the use of two-dimensional geometric shapes in sentences and pictures (e.g., circles, squares and triangles), or non-linguistic typographical objects (e.g., plus signs and asterisks) (Friederici and Levelt 1990, Carpenter et al. 1999, Reichle et al. 2000, Noordzij et al. 2006), see for example Figure 2.1.

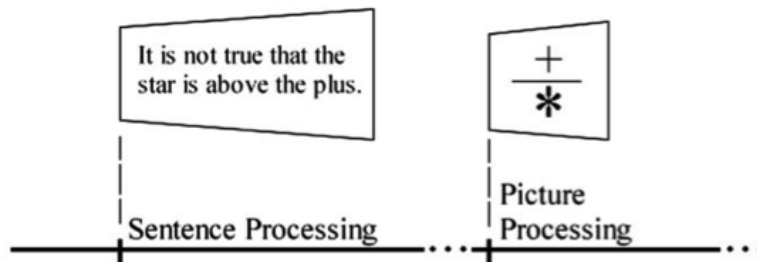


Figure 2.1: Example stimuli from Carpenter et al. (1999)

While the choice of these shapes allows experimental results to unambiguously reflect processes involved in identifying and evaluating geometric spatial relationships and language describing such relationships, it does not represent processes involved in processing spatial relationships in natural language. It is likely that the number of times a person uses spatial language to describe the configuration of geometric shapes is a relatively tiny proportion of the times the person uses spatial

language in her lifetime (Unless, perhaps, if this person is a geometry teacher, or a kindergarten teacher tasked with teaching children the names of shapes.). Instead, people frequently use spatial language to talk about the orientation and configuration of three-dimensional real-world objects, (e.g., cups, buckets, tables and plates).

## 2.2 Features of real objects

When a preposition is used to describe the configuration between real-world objects, geometric explanations fall short. This isn't surprising. Real-world objects, like buckets and plates, are objects with which a person has all sorts of perceptual experience. They have relatively complicated forms (as compared to two-dimensional geometric shapes). They also often have intrinsic functions, which determine the way we expect them to interact with other objects: Bowls and buckets are containers, used for putting objects *in*; tables and plates are surfaces, used for putting objects *on*.

Further, not only do different types of objects have different shapes, but members of the same category of object (i.e., all labeled the same) can vary in shape. Consider the four tables below:



Figure 2.2: Different objects to which the label "table" can apply.

Just as there are prototypical spatial configurations associated with prepositions (see Section 1.2), nominal categories like "table" also are associated with a prototype or an idealized model (Rosch 1975, Rosch et al. 1976, Rosch 1999, Lakoff 1990, Bar et al. 1996, Bar 2004). (For an alternative perspective, see Armstrong et al. (1983)).

The model for "table" will likely contain information about prototypical shape, function and configuration, so that Table 1 is closer to a prototype for the category "table" than Tables 2, 3 and 4 are. These prototypes can interact with spatial words (Coventry et al. 1994, Feist and Gentner 1998). For instance, when a hearer is presented with the sentence "I put the pen in the table" without any visual information, she will likely be surprised by (or even reject) the sentence, due to a mismatch between the representation of a prototype for "in" and the one for "table". However, there are scenes to which this is an appropriate description: for example, when the speaker has placed a pen inside of the drawer of Table 2 or inside one of the diamond-shaped holes in Table 3 (Figure 2.2c).

And finally, a single object may have multiple labels. Each label is associated with implications about its shape and use. For instance, Table 2, Figure 2.2b, may



either be labeled as its basic-level category name, *table*, or its subordinate-level category name, *nightstand* (Rosch 1999). These labels also come equipped with their own prototypical functions, shapes, and so on. Object names will affect spatial language as well. For example, compare the sentences *the pen is in the table* and *the pen is in the nightstand*.

All of these factors affect the way that the language user describes spatial relationships between real-world objects and interprets spatial language involving these objects. The following section expands on the interaction of object knowledge and spatial configuration.

## 2.3 Problems with geometry for explaining spatial language

When geometric definitions (like those presented in Table 1.1) are applied to real-world scenes, complications arise. For instance, Miller and Johnson-Laird (1976) and Herskovitz (1986) posit that a part of a located object need be included in the reference object in order for them to establish an *in* relationship.

But, consider the following scene. For each of the cherries shown in the bowl in Figure 2.3a, the sentence *the cherry is in the bowl* is an appropriate description, even though there are several cherries, like the one highlighted in Figure 2.3a, of which no part is included in the bowl.

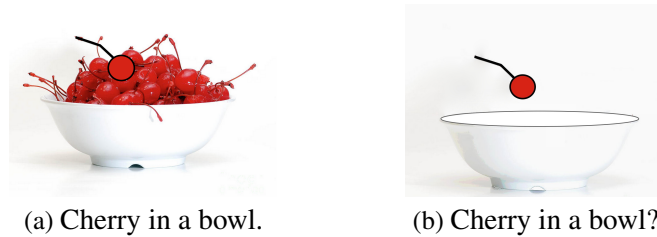


Figure 2.3: Beyond geometry: The spatial position of a cherry in relation to a bowl is only a part of what determines whether it is *in* the bowl

For this cherry, the "in the bowl" designation depends on its relationship to other cherries and their relationship to the bowl. When the other cherries are removed (Figure 2.3a), this cherry is no longer in the bowl, but is "above the bowl" instead. In short, the description of a cherry as being *in the bowl* in Figure 2.3a does not rely merely on the geometric configuration between a located and reference object, but in a complex relationship between a located object, a reference object and other objects (the other cherries). The other objects' (i.e., cherries') role is crucial in determining the relation between the located and reference object, even though they are not mentioned (e.g., "the cherry is in the bowl [by virtue of it being supported by other cherries which are in the bowl]").

Further, there is a functional relationship between the bowl and the cherry. In Figure 2.3a, the bowl's function is to constrain and support the cherry, so that if the bowl were to be moved, the cherry would move accordingly. In Figure 2.3b, the bowl no longer appears to control and support the cherry. Thus, it seems that the determination that the cherry is *in the bowl* in Figure 2.3a is not based solely on the cherry's spatial position with regards to the bowl, but instead on the cherry's

relationship with other objects and on the bowl's functional relationship with that cherry.

Many authors have recognized this problem and consequently propose that extra-spatial factors are involved in the definition of *in*, or at least in extensions of their definitions. These factors include functional notions like support, *location*, *control* or *container/contained* (Miller and Johnson-Laird 1976, Herskovitz 1986, Vandeloise 1991, Feist and Gentner 1998, Garrod et al. 1999, Coventry 1993, Coventry et al. 1994, Coventry 1999, Garrod et al. 1999, Coventry and Garrod 2004, 2005).

## **2.4 Interaction between geometric and extra-geometric features**

The following section explores the way that extra-geometric features, like control/support and object type, interact with geometric information in impacting spatial language.

### **2.4.1 Control**

In a series of experiments, Kenny Coventry, Simon Garrod and colleagues have shown that a reference object's ability to control the location of a located object affects uses of *in* and *on* (Coventry 1993, Coventry et al. 1994, Coventry 1999,

Garrod et al. 1999, Coventry and Garrod 2004, 2005). From the results of these experiments, they have proposed that prepositional denotation is associated with an interaction of geometric and functional features.

For example, Garrod et al. (1999) explored the involvement of functional features in determining the appropriateness of *in* for describing scenes. In a series of experiments, participants were presented with pictures depicting a ball and a bowl in various spatial configurations. The experimenters manipulated the ball's position with regard to the bowl, the number of balls in the bowl, and the possibility of alternative control (a wire connected to the ball). They were asked to rate their confidence that the ball was "in" the bowl.

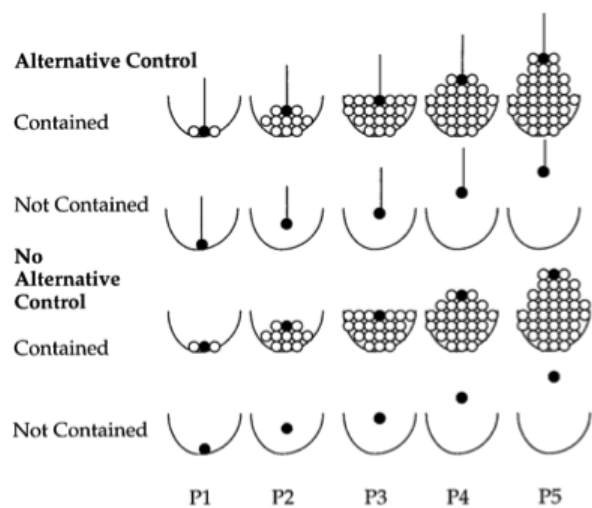


Figure 2.4: Visual materials from Garrod et al. (1999)

The results of the experiment revealed that an interesting interaction of geometric features (the ball's position) and functional features (support by other balls) is

involved in the determination of an *in* relationship: Participants rated position 1 and 2 from Figure 2.4 as being strong examples of a ball *in a bowl*, regardless of alternative control or support; however, when the ball's position ventured into the region outside of the geometric confines of the bowl (as in positions 3, 4, and 5) functional factors were considered. There was a steep decline in the ratings of *in*'s appropriateness for describing the relationship of the ball and the bowl between positions 2 and 3, when the ball was depicted as floating in space and when the ball was shown connected to a wire ("No Alternative Control, Not Contained" and "Alternative Control, Contained/Not Contained", respectively). In the case where the ball sat atop other balls, without any alternative control depicted ("No Alternative Control, Contained"), there was a steadier decline for ratings of *in* appropriateness from position 1 to position 5. In summary, the effect of geometric location and non-geometric support (whether there were other balls underneath the target ball) significantly impacted ratings, whereas the effect of alternative control (whether there was a wire attached to the target ball) did not.

Garrod et al. interpret these results as indicating that geometry is dominant in cases where the depicted spatial relationship between located and reference object is close to a preposition's prototypical spatial sense (1999). In the case of *in*, its prototypical sense is one of geometric enclosure. Positions 1 and 2 show a ball enclosed in a bowl, and are deemed good depictions of *in*ness even when there are functional factors (e.g., a wire attached to the ball) that suggest that the located object's position may not be controlled by the reference object.

Coventry also showed that location control affects the use of *in* (Coventry 1993, Coventry et al. 1994). Subjects are more likely to describe a ball as *in* a reference object when they've seen the ball move in accordance with the reference object, as compared to a static scene (Scenes 1 and 2, respectively, shown in Figures 2.5a and 2.5b). Similarly, when a container is displaced from its canonical orientation (e.g., as a bowl is tilted to its side), participants are increasingly less likely to use *in* to describe the scene (Scenes 3 and 4, shown in Figures 2.5c and 2.5d).

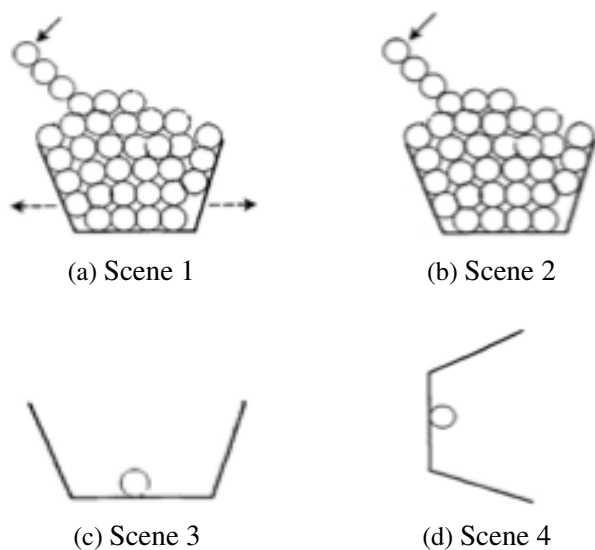


Figure 2.5: Models of video scenes used by Coventry (1993) as depicted in Coventry et al. (1994). Uses of *in* were higher for describing videos of scenes on the left (Scene 1 and 3) and were lower for scenes on the right (Scene 2 and 4)

Coventry and colleagues interpret this latter finding as indicating that the increasing likelihood of a located object's falling out of the reference object decreases the applicability of *in*. These effects, where location control affects the use of *in*, has

also been replicated in children as young as three and a half, which suggests that geometric and extra-geometric features contribute to early stages of prepositional acquisition (Richards et al. 2004).

In a related set of experiments, Michele Feist and Dedre Gentner manipulated the depicted concavity of a reference object along with the animacy of the located and reference objects (2011). The reference object was either a dish or a hand and the located object was either a coin or a firefly. Again, there was an interaction between geometric and extra-geometric factors, where all three factors- concavity, animacy of reference object, animacy of located object- affected the proportion of *in* versus *on* use. As described in section 1, increased concavity resulted in increased uses of *in*. However, there was a significant effect of animacy as well: When the reference object was animate, subjects were more likely to use *in*; conversely, when the located object was inanimate, subjects were more likely to use *on*. Feist and Gentner conclude that these results rely on location control. An animate reference object (a hand) has control over a located object; therefore, objects located within the confines of an animate reference object are likely to be conceptualized as being *in* that object. And, vice versa, an animate located object has control over its position (a firefly can fly away) and is therefore less likely to be construed as being controlled by (and therefore *in*) a reference object.

However, it is arguable that the results from (Feist and Gentner 2011) are not dependent on animacy alone, or even at all. An alternative explanation is that perceived weight contributes to/explains rating patterns for "in". The animate located

object was an insect. If a heavier, flighted animal, like a sparrow, were sitting within the confines of a bowl, "The sparrow is *on* the bowl" is worse than "The sparrow is *in* the bowl". And, conversely, a light inanimate object like a piece of fuzz from a wool sweater is just as likely to be described as being "in the bowl" as being "on the bowl". A heavy object is likely to sink to the bottom of a convex object (so that it is *in* the reference object), while a light object is able to rest on any portion of its surface (so that it is *on* the reference object and perhaps conceived as being supported by the object's material rather than the object itself (see Prasada et al. (2002)). This explanation – that specific features of an object's type will affect the way that it is described spatially – is discussed in the next section.

## 2.4.2 Type

Not only does an object's ability to control the location of another object affect uses of prepositions, but so do the conceived features of a depicted object. As mentioned in Section 2.2, real-world objects are associated with typical uses, shapes and configurations. In short, an object's type "... fundamentally influences how one talks about *where* [it is] located" ( Coventry and Garrod (2004), page 55).

Feist and Gentner (1998, 2011) and Coventry et al. (1994) found that simply changing the label of a the same picture of an object (e.g., as a "bowl", "jug", "plate", "dish", "rock", or "slab") significantly affects whether the preposition "on" or "in" is used to describe a spatial configuration between it and a located



object.

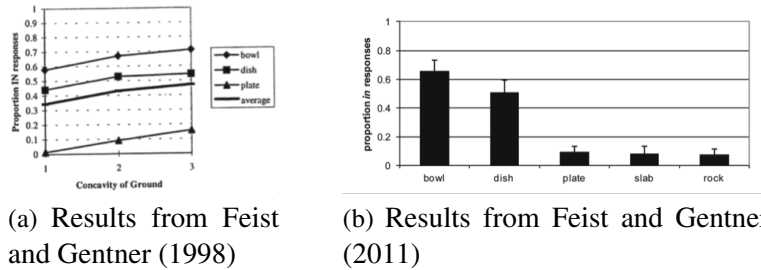


Figure 2.6: Relationship between shape of reference object and label for reference object in determining preposition use

If geometry is central to the processing and use of spatial prepositions, then the shape of the object depicted should have been the most explanatory factor in determining preposition choice. Instead, participants' knowledge of bowls, plates and dishes (how they are used, shaped, etc.) played a key role in determining preposition choice, regardless of the image they saw (Figure 2.6b). However, this knowledge did not play the *only* role. Feist and Gentner (1998) discovered an interaction between concavity level and object label (see Figure 2.6a).

During the discussion of the neurophysiological research in Section 1.5, it was concluded that both spatial language and visual perception feed a shared, amodal/supramodal representation of spatial information. The results from Feist and Gentner (1998) (Figure 2.6a) support this conclusion as well: In their study, visual and linguistic information were found to interact during the evaluation and use of spatial language. This suggests that both language and visual information contribute to a shared representation of a spatial scene, which is used for language evaluation

and production.

Likewise, Coventry et al. (1994), Coventry and Prat-Sala (2001) found that object knowledge affects the use of *in* and *on*, even when a located object is shown in the same spatial arrangement with regards to that referent object (see for example Figure 2.7).

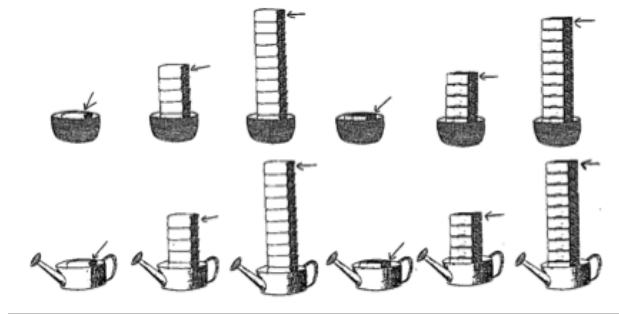


Figure 2.7: Materials from Coventry and Prat-Sala (2001), with objects in a bowl (top) and objects in a jug/pitcher (bottom)

These researchers found that participants rated the highlighted located object (a book) as being *in* the reference object more consistently when the reference object was a bowl than when it was a jug/pitcher. The researchers conclude that this is due to the fact that jugs are typically used for containing liquids, while bowls are often used for containing solids. Interestingly, aside from a liquid vs. solid contrast, variations in the located object's type – i.e., different *types* of liquids or solids – did not significantly affect rating scores. The researchers therefore conclude that the function of the reference object is more important than the located object's is for determining preposition choice. This is similar to the assertions made by Talmy (1983) about a reference object's geometry. He observed an asymmetry between

reference and located objects, where prepositions typically constrain and characterize a reference object's geometry to a greater degree than they do a located object's (see discussion in Section 1.1.1).

Object knowledge has also been shown to affect uses and ratings of the projective prepositions *over* and *under* (Carlson-Radvansky et al. 1999, Carlson-Radvansky and Tang 2000, Coventry et al. 2001, 2010). For instance, Carlson-Radvansky et al. showed participants a picture of a piggy bank and a coin. They varied the position of the slot on the piggy bank, and found that participants based their ratings and uses of *under*, not only on the relation of the coin to the piggy bank, but on the position of the coin to the piggy bank's slot. They showed a similar effect of a toothpaste tube to a toothbrush, where ratings for *under* peaked when the toothpaste tube's end was positioned in between the toothbrush's bristles and its center of mass. The authors concluded that the functional features of an object, e.g. the piggy bank's slot, are considered when determining that object's spatial configuration with another object (1999).

Similarly, Coventry et al. (2010) asked participants to rate the acceptability of the umbrella is *over/above* the man and the man is *under/below* the umbrella to describe a picture. In these pictures, a man holds an umbrella at various angles. In half of the pictures, the umbrella is missing its cloth. In some of the pictures, rain is shown entering the scene from different angles: aimed directly toward the top/center of the umbrella (functional) or aimed at the man (nonfunctional). When a given scene was functional, participants rated sentences containing the prepo-

sitions *under* and *under* more highly than they did when a the scene was non-functional. There was also an interaction between functionality (level of expected protection from rain) and object completeness, where functional scenes (where the angle of the umbrella would protect the man from rain) were rated as worse examples of *over/under* when the umbrella was missing its cloth. The ratings for sentences containing *above* and *below* were less affected by these factors.

In a separate set of experiments, Coventry and colleagues found that there was a significant interaction between the functionality of a scene, the preposition used to describe that scene, and visual fixation patterns (2010). This last finding suggests that extra-geometric factors of objects in a scene not only dictate prepositional choice and ratings of a preposition's appropriateness for describing that scene, but that they actually affect perceptual experience. In other words, people look at objects in a spatial scene differently, depending on the functionality of the scene.

### **2.4.3 Functional Geometric Framework (Coventry and Garrod 2004)**

These facts, taken together, led Coventry and Garrod to suggest that a quasi-geometric framework best accounts for the representation of spatial language. They call their model a "functional geometric framework", which posits that both a geometric *and* functional (object-knowledge-driven) representation are included

in the denotation of spatial prepositions. In this framework, the application of spatial labels to visual scenes is informed not only by the geometric configuration between the objects, but by the dynamic-kinematic features of the scene (e.g., location control), and object information- how the objects in the scene typically function and how they usually interact with other objects.

## **2.5 Electrophysiological processing of spatial language involving real objects: Connecting the *what* and *where* stream**

Taken together, the conclusions from Coventry et al. (1994, 2010) and Feist and Gentner (1998, 2011) demonstrate that object knowledge plays a key role in spatial language use and comprehension. Studying the way that the brain incorporates spatial information with their knowledge of real objects allows a researcher to study neural connections between ventral and dorsal axes. Landau and Jackendoff (1993) argue that because neurons in the dorsal stream are only sensitive to position and not to other visual features, like color, it follows, then, that only rough object information is necessary in the use and understanding of spatial language. Accordingly, Landau and Jackendoff point out that there are very few constraints on what sorts of objects can be used with a particular preposition. The preposition *in*, for instance, can be used with all sorts of two- and three-dimensional objects,

as long as they can be construed as having an interior (1993). In their model, "what" information and "where" information are largely separable, but are linked to each other in a way that allows "where" networks to get a sketchy, geometric representation of object information from the "what" system.

Even though Landau and Jackendoff (1993) argue that a large variety of objects can be used as reference objects to prepositions, behavioral studies like the ones presented in Coventry et al. (1994, 2010) and Feist and Gentner (1998, 2011) show that there are indeed restrictions to the types of objects used with prepositions, making *in the bowl* preferable to *in the plate*, for instance. No electrophysiological study has examined responses to unlikely or impossible spatial phrases, like *in the plate*. Finding a measurable electrophysiological indication of surprise to nouns that represent inappropriate objects after certain prepositions would provide evidence that object ("what") information is used to facilitate the online processing of prepositional ("where") phrases.

One likely electrophysiological candidate for indexing surprise at the onset of an inappropriate reference noun is the N400 response. Marta Kutas and Steven Hillyard first identified the N400 response when they discovered that an anomalous final word in a sentence results in a relatively large centro-parietal negativity, beginning 400 milliseconds after the presentation of the word (1980). For example, the word "socks" elicits larger N400 activity in *he shaved his beard and socks* than it does in *he put on his shoes and socks*.

Since this discovery, N400 activity has been observed in response to all kinds

of meaningful stimuli, including visual/auditory words, sign language signs, gestures, smells, environmental sounds, pictures, videos, and faces (Review in Federmeier and Kutas 1999, Kutas and Federmeier 2000, 2011, Lau et al. 2008, Kuitunen 2007). Focusing on language, when a word is presented after a prime, i.e., another stimulus, like a word or a picture, N400 responses are attenuated when the prime is related to the target stimulus (Review in Kutas and Federmeier 2011). When a word is presented in a sentence, there is an inverse relationship between the word's predictability and the amplitude of the N400 response to that word: The more predictable a word is in a sentential context, whether it be due to its position, cloze probability, or semantic and pragmatic appropriateness, the lower the N400 response (Van Petten 1995, Van Petten et al. 1999, Federmeier and Kutas 1999, Hagoort and van Berkum 2007, Reviews in Federmeier and Kutas 1999, Kutas and Federmeier 2011, Lau et al. 2008, and Kuitunen 2007).

Rommers et al. (2013) discovered that the prediction of shape features modulates the N400 amplitude of the final noun in sentence contexts. This study revealed an attenuated N400 response to a noun that is unrelated from an expected noun in all features except for shape, as compared to a noun that is unrelated in all features. Below are three of the sentences used (translated from Dutch):

- **Target/Correct:** *The couple was unlucky weather-wise and got married in the pouring rain*
- **Related Shape:** *The couple was unlucky weather-wise and got married in the pouring chocolate-sprinkles*

- **Unrelated:** *The couple was unlucky weather-wise and got married in the pouring red*

The researchers speculate that the priming of an upcoming noun's shape reveals a link between language and visual environment, where activation of shape information can be used for object recognition. Predicting an object's shape accelerates the process of finding that object in the visual world. In other words, predicting *what* objects are helps a person to find *where* objects are. This seems particularly relevant during the processing spatial phrases, since these phrases are often used to orient and locate objects in the visual world. For example, while a person's is searching for her keys, a sentence beginning *Your keys are on...* is likely to prevent her from digging through her purse, even before the sentence is completed and the reference noun is revealed.

More direct evidence of an online connection between *what* and *where* streams during the processing of visuo-spatial information involving real-world objects comes from a study by Carlson et al. (2002). These researchers explored ERPs to photographs of real-world, three-dimensional objects in different spatial configurations. Participants were tasked with determining whether each picture depicted a spatial relationship described by a previously presented sentence, for instance, *the ball is above the watering can*. Pictures depicted the two objects in different configurations, including 1) a canonical and absolute *above* configuration, where the watering can was presented upright, with its opening at the top, with its spout to the right, and with the ball positioned directly above its opening; 2) a noncanon-



ical, absolute *above* position, where the watering can was rotated 90° clockwise, with its spout pointed downward, its handle at the top, and with the ball positioned directly above its handle; 3) a noncanonical, intrinsic *above* configuration, where the rotated 90° clockwise, with its spout pointed downward, its handle at the top, and with the ball positioned to the right of the watering can's opening, so that it would be *above* the watering can's opening if the entire picture were rotated 90° counterclockwise.






Placement	Picture
Canonical Above	
Canonical Not Above	
Noncanonical Absolute Above	
Noncanonical Intrinsic Above	
Noncanonical Not Above	

Figure 2.8: Materials from Carlson et al. (2002), with a ball and a watering can in different *above* and *not-above* configurations

Canonical versus non-canonical orientations of the reference object (Compare top two pictures in Figure 2.8 to bottom three pictures) yielded significant effects on the central parietal positive deflection, which they called a P3 response. The P3 peaked in centro-parietal sites about 400ms post-picture onset. Canonical orientations of the reference object resulted in a larger P3 than non-canonical orientations did. They interpret this result to reveal processes in identifying the reference object, so that easier, clearer identification yielded a more robust P3.

Processes involved in computing the previously read spatial phrase (e.g., *the ball is above the watering can*), and comparing it with the spatial scene presented in the picture were measurable by positive-going slow wave activity in occipital and lateral parietal sites, peaking about 600ms post-picture onset, where canonical and intrinsic/absolute representations of *above* (See topmost configuration in Figure 2.8 for an example) yielded a slow wave with the highest amplitude. Carlson et al. (2002) suggest that when participants are tasked with determining whether a given scene accurately represents an *above* relationship, they must compare the perceived scene with internalized spatial templates for *above*. The better the perceived scene matches internalized templates, the stronger the response.

Although both positivities (the P3 and parietal-occipital slow wave) peaked at similar times and at similar electrode sites, a post-hoc ANOVA comparing features of the waves (the conditions which elicit them, the electrodes in which they were most prevalent, and the times at which they peak) revealed them to be significantly different from one another. Consequently, the authors conclude that the P3 and parietal-occipital slow-wave represent two different processes. The earlier P3 process is involved in identifying the object ("what" the object is) and the second, slow-wave process, is involved in assigning a reference frame to the object and matching that to a particular spatial description ("where" the object is). Although the post-hoc ANOVA confirmed that these responses were separable, the authors concede that processes involved in indexing and categorizing the reference object ("what" processes) likely impacted the processes involved in matching spatial templates to the scene ("where" processes). This explanation is supported by

the fact that these responses show parallel modulations in the different conditions- i.e., highest amplitude in canonical, absolute conditions and attenuated amplitudes in both non-canonical, intrinsic conditions and *not above* conditions. Unfortunately, distinctions between canonical and non-canonical representations of both the reference object and the spatial relationship were always determined by the orientation of the reference object; therefore, it is impossible to fully differentiate "what" and "where" processes in their study. Had they sometimes manipulated other features of the reference object (e.g., its shape or its type) their interpretation would have more support. Still, their results are consistent with the idea that both "what" processes and "where" processes are involved in applying a spatial relationship to a perceived spatial scene so that "what" processes impact "where" processes.

Coventry and Garrod (2004) incorporate features of the dual-stream hypothesis into the functional geometric framework (described in Section 2.4.3. In their model, when a person is perceiving a visual scene, the "what" system returns information necessary for the processor to identify objects while the "where" system returns features necessary for the processor to determine how to interact with them. They argue that both of these streams must be involved in the processing and use of spatial language since the functional features of an object ("what" the object is) impacts the use of spatial language describing it. In another paper, Coventry et al. describe the implementation of this framework in a computational model of visuo-spatial and spatial language processing 2005. This model is equipped with knowledge of typical spatial and functional relationships between objects, so

that each spatial sentence is associated with the typical situation in which objects are placed and with information regarding how objects typically interact with one another. The model accurately predicts the way that objects will interact in a visual scene and accurately applies spatial labels (*above/below/over/under*) to the scene.

## Chapter 3

### Experiment

*The previous chapters have shown: the processing of spatial language and visuo-spatial scenes activate overlapping regions in the parietal lobe; object knowledge contributes to the processing and use of spatial language. Therefore, the manipulation of objects' features in pictures and in language should result in an electrophysiological effect during the processing of spatial language. Measuring the timing and topography of this effect will elucidate the interaction between object knowledge and spatial language during processing, and how visual information and linguistic information interact. In order to get a better understanding of the interaction between visuo-spatial information and spatial language information during the processing of spatial phrases, an Event-Related Potential experiment was conducted. In this experiment, electrophysiological brain responses were recorded as participants read spatial phrases after seeing photographs of objects in different spatial configurations. This chapter introduces the study and details the experiment's methods.*

## 3.1 Introduction

### 3.1.1 Background

Previous behavioral research has shown that the geometric and functional features of a reference object can determine the acceptability of a prepositional phrase headed by *in* or *on*, so that *in the bowl* is considered more acceptable than *in the plate* is; and, conversely, *on the plate* is more acceptable than *on the bowl* is (Coventry and Prat-Sala 2001, Coventry et al. 1994, Feist and Gentner 1998, 2001, 2011). This suggests that language users are sensitive to an object's representation when they are processing and producing spatial language.

It is likely that when a spatially inappropriate phrase, like *in the brick*, is encountered, there is a measurable neurophysiological indication of surprise at the onset of the noun *brick* when it is presented the preposition *in*. To date, no neurophysiological study has examined brain responses to phrases where reference object features are inappropriate for a preposition. The nature and timing of neural responses to these phrases can uncover the mental processes involved in semantically decoding prepositional phrases about real-world objects, perhaps revealing the activation of spatial-image-formation processes that are implicated during the processing of spatial language describing geometric objects (Carpenter et al. 1999, Mellet et al. 2000, Creem and Proffitt 2001, Mazoyer et al. 2002, Formisano et al. 2002, Trojano et al. 2006). Further, finding a neurophysiological indication of sur-

prise at the onset of nouns that represent inappropriate object types for particular prepositions (e.g., at the onset of *brick* in *in the brick*) would provide evidence that object information is used to facilitate the on-line processing of prepositional phrases, supporting theories of prepositional semantics that incorporate both functional and geometric features into the representation of prepositions, like the functional geometric framework proposed by Coventry and Garrod (2004) (See Chapter 2).

The amplitude of the N400 response (described in Section 2.5 in Chapter 2) to reference nouns may be susceptible to the semantics of the preceding preposition, so that the N400's amplitude may increase when the object that the noun represents is functionally and/or spatially inappropriate for the preposition's denotation (e.g., *in the brick*). Discovering an N400 response to a noun whose lack of appropriateness is solely controlled by the semantics of a preposition (like *brick* after *in*) would provide empirical support for a large body of work that has promoted the rich semantic features of prepositions (See Chapter 1)). This finding would be noteworthy because prepositions are closed-class lexical items. Closed-class items are often ignored when neurophysiology is used to study semantic processing because they are associated with their grammatical rather than their semantic functions. Consequently, the role that prepositional semantics plays in the construction of a sentence's meaning and in the expectations of upcoming words has not been considered in the literature. If modulation or amplification of neurophysiological responses results simply as a function of the semantic features of a preposition (*in the brick* versus *on the brick*), this will demonstrate that there is

more to semantic processing than the incorporation and activation of nominal and verbal features. This finding would shed light on sentence processing, in general, but also specifically on the processes involved in semantically decoding spatial scenes and determining which nouns are spatially and functionally appropriate for a given preposition.

As described in Section 2.5, Rommers et al. (2013) found that the prediction of shape features of an upcoming noun lead to N400 effects, so that an unpredictable noun yields a smaller N400 response when its shape matches the shape of the predicted noun (as compared to an unpredictable noun whose shape does not match the shape of the predicted noun). Since shape features are at least partially responsible for the determination that a reference noun is inappropriate after a preposition, spatially mismatching nouns (e.g., *in the plate*) may elicit amplified N400 responses, suggesting that prepositions (on their own) can prime the shape features of certain nouns.

Another neurophysiological response that may be impacted by the semantics of prepositional phrases is the parieto-occipital slow wave, introduced in Section 1.5.1. Noordzij et al. (2006) assert that parieto-occipital negative slow-wave activity indexes spatial-image formation during spatial-language processing. A phrase like *in the bucket* corresponds with a clear spatial configuration, where some located object is inside of a container reference object, a bucket. This clear spatial configuration is likely associated with a clear spatial image. A phrase like *on the bucket*, on the other hand, does not correspond with an obvious spatial scene. There are



situations in which it does map to visual information - for instance, an object can be located *on* a bucket when the bucket is upside-down - but these situations are less common and less familiar than spatial match cases. The spatial image associated with *on the bucket* is therefore more difficult or even impossible to construct (without additional input, like being told that the bowl is upside-down).

If its amplitude increases as a function of increasing imageability, it should be larger for expected phrases like *in the bucket* than for unexpected and abstract phrases, since *in the bucket* maps to a clear image, built from frequent *in the bucket* perceptual experiences. The findings from Carlson et al. (2002) (See summary in Chapter 2, Section 2.5) provides support this- where larger parieto-occipital slow-wave activity indicates stronger imageability. However, if parieto-occipital slow-wave amplitude increases as a function of increasing difficulty or effort in image formation, it should be larger for unexpected spatial phrases like *in the brick* or abstract spatial phrases like *in the moment* than for expected spatial phrases like *in the bucket*.

Behavioral research has also shown that the visual features of an object impact the way that spatial language is used and interpreted when it involves that object as the reference noun. For example, Feist and Gentner (1998) discovered an interaction between an object's visual features and the object's label when participants were asked to assign a spatial label (*in* or *on*) to a scene describing that object. While some previous literature (e.g., Carlson et al. 2002) has explored the interaction between visual manipulations of objects and spatial language, these manipula-

tions have always been geometric (e.g., orientation). To date, no neurophysiological study has examined whether other visual features (e.g., shape) of an object impacts spatial language processing. A measurable change in neurophysiological responses during the processing of spatial language describing real-world objects based on the visual manipulation of these objects would: A) support theories that claim that spatial language and visual perception feed a shared supramodal representation of spatial information (Struiksma et al. 2009, 2011); and B) reveal an interaction between "what" processes and "where" processes during spatial language processing (Landau and Jackendoff 1993, Carlson-Radvansky et al. 1999, Carlson et al. 2002, Coventry and Garrod 2004, Coventry et al. 2005). As shown by Feist and Gentner (1998, 2011), Coventry et al. (1994), the shape of objects in a visual depiction affects the rating and production of *in* and *on*. As the concavity depicted in the picture of an object increases, the rating and use of *in* increases, no matter the label given for the depicted object and vice versa for the rating and use of *on*. Further, they discovered an interaction between object label and object shape, so that a less concave object called a "bowl" was deemed more appropriate for *in* than a more concave object labeled as a "plate".

Priming effects measured by the attenuation of the N400 response occur across modalities, from pictures to words/sentences and vice versa (Nigam et al. 1992, Ganis et al. 1996). Therefore, the size of N400 responses to *in* and *on* may depend on the visual depiction of objects. The shape of the object's depiction might impact responses. For instance, plate 1 (below) may prime *in* less effectively than Plate 2 does. If so, N400 effects at *in* would reflect this, so that the N400 response to *in*

would be larger after Plate 1 is presented than after Plate 2 is.

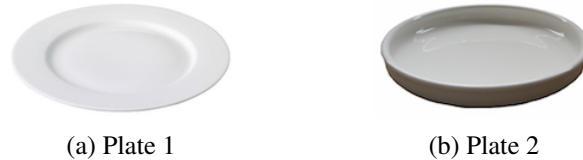


Figure 3.1: Picture primes for prepositions: Plate 1 (left) should be a better prime for *on* and Plate 2 (right) should be a better prime for *in*

This effect would show that the processes used to make judgments about which preposition to use to describe spatial scenes involving different object types, as reported in Feist and Gentner 1998, 2011, Coventry et al. 1994, are not simply a post-lexical or meta-linguistic processes, but are instead observable during on-line processing of prepositions and prepositional phrases.

Not only might the visuo-spatial features of an object impact responses to prepositions, but the *type* of object shown in a picture might also affect responses to prepositions, so that pictures of container objects (e.g., bowls) prime *in* and surface objects (e.g., plates) prime *on*, no matter the configuration of the object in the picture. This finding would provide support for theories such as the functional geometric framework, which emphasizes the importance of object knowledge (i.e., its typical function, shape, interaction with other objects) in the lexical representation of prepositions (Coventry and Garrod 2004).

Thus far, no ERP study has demonstrated that the semantic representation of a closed-class item is primed by sentential or visual context during the online pro-

cessing of sentences. DeLong et al. (2005) show that the articles *a* and *an* can be primed by context; however, the context serves to activate the representation of the noun following the article, and not the article itself. For example, the sentence *It was a breezy day, so Billy decided to go outside and fly ...* primes the noun *kite* more than it does *airplane*. Consequently, this sentence also primes the article *a* more than the article *an*. This is reflected in N400 effects, where the N400 response to the article is attenuated when it agrees with the predicted upcoming noun. Their finding is encouraging, since it suggests that the amplitude of N400 responses to closed-class items is susceptible to context effects; however, it does not show that the semantic representation of closed-class items are primed by context. Modulated N400 responses to *in* and *on*, dependent on previously-viewed pictures of objects would be an exciting result, since it suggests that there is a semantic representation of prepositions, which is activated by visual primes.

The N400 response to reference nouns may be affected by the visual depiction of objects as well. There may be an effect of typicality, where a more typical visual representation of a reference object (e.g., the less concave plate, Plate 1, Figure 3.1a) is a more effective prime than an atypical one is (e.g., the more concave plate, Plate 2, Figure 3.1b). This finding would suggest either that the representation of *plate* is associated with particular conceptual, visuo-spatial features, or, that upon seeing Plate 1, the label *plate* is activated to a greater degree than the level of activation induced by Plate 2. This latter possibility could result from Plate 2 being a weaker representation of *plate* or because Plate 2 activates multiple labels -*dish, bowl, tray, etc.*- which create competition, making the re-

trieval of *plate* more difficult.

For reference nouns, there may also be an interaction between phrase type and picture type. Above, it was suggested that the depiction of objects' spatial features, for example concavity, might affect N400 responses evoked by the prepositions in each sentence. There may also be neurophysiological effects of the visual depiction of objects downstream from the prepositions, at the onset of the reference objects. If the entire phrase is integrated with the preceding picture, then there should be a smaller N400 for the reference noun *plate* in the phrase *in the plate* when it follows a picture of a concave plate like Plate 2, Figure 3.1b, than when it follows a flat plate, like Plate 1, Figure 3.1a. If, on the other hand, the N400 to *plate* in *in the plate* is equivalent to the N400 response to *plate* in the phrase *on the plate* and in the non-spatial control *and the plate* after the presentation of a photograph of a concave plate, this would suggest that it is simply the atypicality of a concave plate that is fueling a larger N400 response.

### 3.1.2 Current study

In order to research the way that spatial language involving real-world objects is processed on line, and to see how this processing is impacted by the visual depictions of objects, the experiment presented in this dissertation examines brain responses of native English speakers to phrases containing spatial language after seeing different photographs of objects.

The study utilizes electroencephalography (EEG) in order to measure neural activity. EEG can be used to study the brain's responses to stimuli in real time by recording ongoing electrical activity as a participant is presented with a stimulus. Once the stimulus has been repeated numerous times, an average is made of a segment of EEG activity, time-locked to the onset of the stimulus of interest. This average is called an Event-Related Potential (ERP), and it indexes the brain's response to a particular event. Averaging across many trials (word, sentences or pictures) is undertaken to remove noise (i.e., brain activity that is unrelated to the stimulus of interest).

In this study, EEG responses are recorded as participants read phrases. Experimental phrases contain a preposition, either *in* or *on*; control phrases contain the conjunction *and*. Most of the experimental sentences are locative, where a located object's position is described in relation to a reference object. Locative phrases are subdivided into semantically appropriate and inappropriate sentences; semantic appropriateness depends on the interaction of the reference object and the preposition (e.g., *in/on the bowl/plate*). Along with locative prepositional phrases, idiomatic phrases containing abstract reference nouns are also used. These phrases are also appropriate or inappropriate, depending on whether the reference noun is typically used in an idiomatic expression with the preceding preposition (e.g., *in/on the wrong/mend*).

Before each phrase is presented, participants are presented with photographs of objects. In the photographs, objects are either depicted in an *in* configuration or

an *on* configuration, so that photographs of objects either match the preposition in the phrase (are spatially matching) or do not match the preposition in the phrase (are spatially mismatching).

The project seeks to answer the following questions:

1. What neural responses are involved in the determination that an object is an appropriate fit for a preposition?
2. How does the visual depiction of objects impact neural responses during spatial language processing?

To answer these questions, the study will explore the way manipulations to linguistic and visual stimuli impact two ERP components: the N400 response and parietal-occipital slow-wave activity (described in Section 1.5.1 and 2.5 in Chapters 1 and 2, respectively). It is predicted that both responses will be impacted by manipulations to pictures and phrases in this study. Specifically, the following hypotheses are made for each of the two research questions:

1. ***What responses are involved in the determination that an object is an appropriate fit for a preposition?***
  - a. Spatially mismatching nouns (e.g., *on the bowl*) will result in larger N400 responses than spatially matching nouns (e.g., *in the bowl*).
  - b. All of the prepositional phrases will evoke a parieto-occipital slow wave and the non-spatial sentences will not.

- c. Increased parieto-occipital slow-wave activity will be generated by spatially appropriate phrases like *in the bucket* than for spatially inappropriate phrases.

**2. *How does the visual depiction of objects impact responses during spatial language processing?***

- a. The amplitude of the N400 response to *in* and *on* will depend on both the object in the previously viewed picture and the object's configuration. For instance, when a picture depicts an *in* object (e.g., a bowl), N400 responses to *in* will be reduced (as compared to responses to *in* after a picture of an *on* object is presented), and will be further reduced when that *in* object is displayed in an *in* configuration (e.g., open side up).
- b. There will be an inverse relationship between typicality and N400 amplitude, so that the more typical an object's depiction in a photograph is, the smaller the N400 amplitude to its label (the reference object) will be.
- c. There will be decreased N400 responses to reference nouns when they follow a picture of a spatially matching object than when they follow a spatially mismatching object.
- d. Parieto-occipital slow-wave activity will increase when spatial phrases follow pictures than when they do not. This difference should not be



found for non-spatial sentences.

## 3.2 Participants

Thirty-three native-English-speaking adults ( $\mu = 24;8$  years, 22 females) completed the experiment. The data from 5 participants were excluded from analysis, either because they had immigrated to the United States as an adult ( $N = 2$ ) or because their EEG data contained excessive noise from poor impedances and from other factors like blinking and other facial movements ( $N = 3$ ).

Of the 28 participants ( $\mu = 24;11$  years, 18 females) whose data were included in the final analysis, 27 were right-handed. None of them had ever been diagnosed with a neurological, learning, reading or attention disorder. All participants had 20-20 eyesight or corrected vision. Participants with corrected, near-sighted vision ( $N = 11$ ) wore glasses or contacts during the experiment so that they could comfortably read the phrases and see the pictures.

Of the 28 participants whose data were included in the analysis, all had completed high school or had passed a high-school equivalency exam. All of them were born in the United States. Twenty-seven of them had been exposed to English from birth. One participant's parents had emigrated from Poland, so that her first language was Polish. But, from pre-school years on, she was immersed in an English-speaking environment so that she now considers herself a native English speaker whose fluency in English is better than Polish. See Table 3.1 below for

participant details.

### PARTICIPANT INFORMATION

	AGE	SEX	HANDEDNESS	LANGUAGE
N=28	$\mu= 24;10$ yrs	18 F	27 Right-Handed	18 Monolingual
	Range= 20-41 yrs	10 M	1 Left-Handed	7 Bilingual <sup>1</sup>

Table 3.1: Details about participant population: age, sex, handedness, and language background.

Participants were paid \$10 per hour for a 2 to 2-and-a-half-hour session in the lab. Before beginning the experiment, each participant spent about 15 minutes completing paperwork- an informed consent form and a background questionnaire. This was followed by a 30-to-40-minute process of setting up equipment and adjusting the electrode net so that it fit the participant correctly and comfortably and so that electrode impedance levels were below 60 k $\omega$ . The experiment itself lasted an hour and twenty minutes.

IRB approval (protocol # 11-11-336-0135) was granted by the CUNY Graduate Center and all participants signed an informed consent form (See Appendix C for a copy of the consent form provided to participants).

<sup>1</sup>3 Spanish-English, 2 Polish-English, 1 German-English

## 3.3 Stimuli

### 3.3.1 Pilot experiment

A pilot, sentence-rating experiment was used to test all the stimuli used in this ERP study. A thorough description of the pilot experiment is presented in Appendix A. In the pilot study, participants were presented with photographs of objects with varying spatial features and/or in different spatial configurations, and then were presented with sentences containing spatial and abstract uses of the preposition *in* or *on*. Participants also read control, non-spatial sentences containing the conjunction *and*. Participants were asked to rate how unexpected or surprising they found each sentence. Rating scores, reading times, and rating times were recorded and analyzed. Sentence-rating results confirmed that certain nouns were considered more or less appropriate reference objects for *in* and *on*. Rating and reading times showed that different depictions of objects in pictures impacted the processing of spatial sentences.

### 3.3.2 Linguistic Stimuli

Linguistic stimuli consisted of 144 prepositional phrases and conjunction phrases (See Appendix B for the full list of items). All phrases fit the following frame:

The NONCE NOUN PREP/CONJ the NOUN

### 3.3.2.1 Prepositions and conjunctions

The prepositions used were either *in* or *on*. The conjunction used was *and*.

### 3.3.2.2 Reference nouns

Reference nouns, following the preposition or conjunction, were selected from those used in the pilot study described in Appendix A.

Forty-eight reference nouns were used with prepositions: 12 concrete *in* nouns, 12 concrete *on* nouns, 12 abstract *in* nouns, and 12 abstract *on* nouns. When each of these nouns was paired with *in* and *on*, 96 prepositional phrases were created: 24 concrete space match, 24 concrete space mismatch, 24 abstract match and 24 abstract mismatch. Matches were phrases where *in* nouns were paired with *in* and *on* nouns were paired with *on*. Mismatches were phrases where *on* nouns were paired with *in* and vice versa. The following are examples of preposition phrases used in the experiment:

1. **Concrete Space Match:** *in the bowl / on the plate*
2. **Concrete Space Mismatch:** *on the bowl / in the plate*
3. **Abstract Match:** *in the moment / on the verge*
4. **Abstract Mismatch:** *on the moment / in the verge*

Twenty-four concrete nouns (12 *in* nouns and 12 *on* nouns) were selected based on their referents having certain spatial/functional properties listed in Herskovitz

(1986), making them more likely to be conceptualized as *in* objects or *on* objects: *in* nouns represented either "containing" objects (e.g., *bucket, bowl*) or "embedding" objects (e.g., *milk, coffee*); *on* nouns all represented "supporting" objects (e.g., *table, plate*).

As described in Chapter 2, previously published experiments measured the perceived appropriateness of using *in* or *on* with different nouns and/or measured participants' rates of using *in* or *on* with different nouns, for example in Feist and Gentner (1998, 2011). Some of the nouns used in the current study were also used in these studies. The rating/use patterns reported in these studies confirmed that they were appropriately categorized as *in* nouns or *on* nouns, respectively, since they were shown to be rated significantly higher (i.e., considered more appropriate) following *in* or *on*, and/or because they were reported as being paired significantly more frequently with *in* or *on*.

For nouns that had not been used in previous rating/production experiments, the rating patterns from the pilot experiment described in Appendix A confirmed that participants considered each of them to be significantly more appropriate following one preposition (e.g., *in*) more than the other (e.g., *on*) (See Figures A.13a and A.13b for rating patterns for individual nouns).

Abstract nouns used in idiomatic/abstract phrases were selected from spatial metaphors described by Lakoff (1994), Lakoff and Johnson (2008), and Tyler and Evans (2003). Most *in* abstract nouns were listed as TIME IS A CONTAINER (*afternoon*) or STATE IS A CONTAINER (*dark*) metaphors by Lakoff and Johnson (2008).

Most *on* abstract nouns were listed as STATE IS A LOCATION (*mend*) or ACTION IS SELF-PROPELLED MOTION, SO THAT A STAGE IN ACTION IS A LOCATION ALONG A PATH (*rise*) metaphors by Lakoff (1994). All the abstract phrases (abstract match and mismatch) were tested in the behavioral pilot study. Rating patterns showed that participants were familiar with all of the abstract/idiomatic expressions; they rated abstract mismatch phrases (*on the moment/in the verge*) as significantly more surprising than abstract match phrases (*in the moment/on the verge*). For the sentence-rating patterns, see Section A.3.1 in Appendix A.

Conjunction phrases were of two types: 1) Non-spatial matches for the concrete spatial phrases, containing the 24 concrete *in* and *on* nouns (see Table 3.2); 2) Control<sup>2</sup> items, containing 24 nouns that were matches for neither *in* nor *on*, and, as such, did not represent containing/embedding objects or supporting surfaces (Herskovitz 1986). The following are examples of conjunction phrases used in the experiment:

1. **Conjunction Match:** *and the bowl / and the plate*
2. **Conjunction Control:** *and the button / and the pin*

To ensure that concrete and abstract reference nouns were appropriately categorized as concrete and abstract, respectively, concreteness ratings were analyzed. These ratings (on a scale of 1-5, where 5 is most concrete) were obtained from a database of ratings for 40,000 American English words of different lexical cate-

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<sup>2</sup>These phrases are sometimes referred to as "filler" items, since their primary purpose was to ensure that the number of *in* and *on* phrases presented to participants matched the number of *and* phrases.

gories (Brysbaert et al. 2014). Brysbaert et al. collected concreteness scores from over four thousand participants using Amazon Mechanical Turk. All of the words used in this study were found on the Brysbaert et al. (2014) list; however, a few of the abstract nouns (e.g., *make* and *rise*) were categorized as verbs, and others (e.g., *red* and *dark*) were categorized as adjectives. Two-tailed t-tests were used compare scores, in order to establish that concreteness scores for concrete nouns were significantly higher than concreteness scores for abstract nouns and to confirm that concreteness scores were statistically equivalent for the following sets of nouns: concrete spatial nouns versus concrete non-spatial nouns, concrete *in* nouns versus concrete *on* nouns, and abstract *in* nouns versus abstract *on* nouns.

Concreteness ratings confirmed that nouns had been correctly categorized. The concreteness ratings for concrete nouns ( $\mu= 4.83$ ,  $\sigma= 0.11$ ) were significantly higher than concreteness ratings for abstract nouns ( $\mu= 3.19$ ,  $\sigma= 0.88$ ) ( $p < 1.0 \times 10^{-11}$ ). Concreteness ratings for concrete spatial nouns ( $\mu= 4.83$ ,  $\sigma= 0.11$ ) were equivalent to ratings for concrete conjunction nouns used in control phrases ( $\mu= 4.84$ ,  $\sigma= 0.13$ ),  $p > 0.8$ . Concreteness scores for concrete *in* nouns ( $\mu= 4.85$ ,  $\sigma= 0.12$ ) were not significantly different from concreteness ratings for concrete *on* nouns ( $\mu= 4.82$ ,  $\sigma= 0.12$ ),  $p > 0.5$ , and concreteness ratings for abstract *in* nouns ( $\mu= 3.03$ ,  $\sigma= 1.08$ ) were not significantly different from concreteness ratings for abstract *on* nouns ( $\mu= 3.34$ ,  $\sigma= 0.63$ ),  $p > 0.3$ .

Table 3.2 presents the full list of reference nouns used.

CONCRETE <i>IN</i> NOUNS	CONCRETE <i>ON</i> NOUNS	ABSTRACT <i>IN</i> NOUNS	ABSTRACT <i>ON</i> NOUNS	CONTROL <i>AND</i> NOUNS	
bag	bench	afternoon	double	apple	hammer
bowl	block	dark	hour	banana	knife
bucket	brick	evening	internet	brush	lamp
coffee	ceiling	future	make	button	match
cup	fence	know	mark	candle	pen
drawer	mat	majority	mend	candy	pencil
jar	pillow	mix	rise	carrot	penny
milk	plate	moment	run	chalk	pin
mug	rock	morning	take	cloud	plant
paint	roof	movie	uptake	curtain	rope
sugar	rug	red	verge	flag	string
tub	table	wrong	whole	guitar	sun

Table 3.2: Full list of reference objects used for ERP study

### 3.3.2.3 Located nouns

Thirty-three (33), monosyllabic words (e.g., *toose* and *wid*) were randomly combined with the preposition and conjunction phrases to create phrases of the type *the toose in the afternoon* and *the wid and the plate*. In each prepositional phrase, the nonce word acted as the located object. Nonce words were used in this slot, rather than real English nouns, to prevent the located nouns from making a semantic contribution to the phrase. This ensured that predictions about the upcoming preposition in a phrase were restricted to those created by the visual stimulus preceding it, and predictions about the upcoming reference noun were restricted to those created by the combination of the preceding visual stimulus and the preposition/conjunction.



The phonological properties of these words were controlled to match those of real English words. See Section A.2.2.1 in Appendix A for details.

### **3.3.3 Visual stimuli: Photographs**

One hundred and eight (108) different photographs of objects were displayed to participants in this experiment. Most of these photographs were found on Google images. When that was not possible, photographs of objects were taken using the built-in camera on a Google tablet, a Nexus 7. In most of the photographs, objects were depicted on a white backdrop. When it was impossible for objects to be displayed on a white background, for instance, when the objects themselves were white (e.g., *sugar* or *cloud*), the picture was edited to make background information minimally distracting. All photo-editing was performed in iPhoto 9.5.1 and/or Preview 7.0.

#### **3.3.3.1 Photographs of concrete objects**

Two photographs were created for each of the reference noun objects used in concrete phrases (24 concrete *in/on* nouns (e.g., *bag/bench*) and the 24 control/filler *and* nouns (e.g., *apple*), N= 96. For the conjunction phrases used as control/filler items, each photograph of the reference object displayed a different token of that object, for instance a green apple versus a red apple and an electric guitar versus an acoustic guitar, N= 48. These 48 photographs were also used as the unrelated,

mismatched photographs of objects shown before prepositional phrases in 25% of trials. See Section 3.4 for details about different item types. For the concrete nouns used in concrete *in/on* phrases (and their conjunction phrase matches), two different versions of objects were displayed: an *in* version and an *on* version, N= 48. *In* and *on* versions of each object were created by manipulating various features of the objects, including the object's geometric shape, the object's configuration, and/or the object's type.

Figure 3.2 shows examples of photographs of reference objects in concrete *in/on/and* phrases, to show how each were manipulated to make an *in* and *on* version of each.







OBJECT	MANIPULATED FEATURE	<i>IN</i> VERSION	<i>ON</i> VERSION
<i>bowl</i>	configuration		
<i>plate</i>	shape		
<i>table</i>	type		

Figure 3.2: Example photographs of concrete reference objects

When object type was altered, as it was for the noun "table" in Figure 3.2, the depicted object's function was also oftentimes intrinsically altered. For instance, the *on* version of "table" depicted in Figure 3.2 is a table that would likely be used to eat *on* or store items *on*, while the *in* version of "table" is a desk-like object that would likely be used for writing *on*, but also for storing items *in*.

### 3.3.3.2 Photographs of abstract objects

For the abstract spatial sentences, 12 pictures of 2- or 3-dimensional objects without obvious labels were used. Six *in* objects and six *on* objects were chosen. Each of these objects was selected as construable as an *in* or *on* object based on its geometric shape. Each *in* object had an obvious interior space; each *on* object did not (see Figure 3.3 for example photographs).

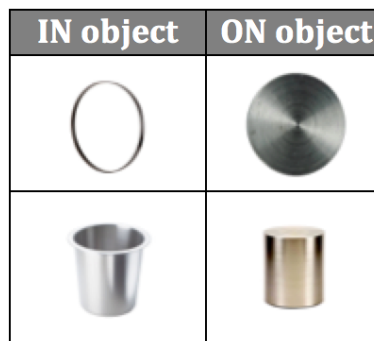


Figure 3.3: Example photographs of abstract objects

### 3.3.4 Auditory stimulus

A 500-millisecond-long 400Hz simple sine wave tone was used to cue upcoming linguistic stimuli at the beginning of the trials that did not have pictures (the "no picture" condition). The tone was created using SoundForge v. 4.5. This tone was presented simultaneously to the presentation of a blank white screen on the computer monitor and prepared participants for an upcoming stimulus without semantically priming them for it with any meaningful auditory or visual information

### 3.4 Item types

Four possible types of audio-visual stimuli preceded each phrase. Since there were 144 different phrases, there were 576 total items.

Figure 3.4, below, shows example items for the concrete prepositional phrases. The three photographs shown before the concrete prepositional phrases consisted of:

1. A spatially matching version of the object in the phrase;
2. A spatially mismatching version of the object in the phrase;
3. A random, unrelated object.









Spatial Match: <i>the flep on the plate</i>		Spatial Mismatch: <i>the flep in the plate</i>	
No Picture		No Picture	
Object Match, Spatial Match		Object Match, Spatial Match	
Object Match, Spatial Mismatch		Object Match, Spatial Mismatch	
Object Mismatch		Object Mismatch	

Figure 3.4: Photographs for the concrete prepositional phrases *The flep on the plate* and *The flep in the plate*

Figure 3.5 presents example items for abstract spatial phrases. The three photographs shown before the abstract prepositional phrases consisted of:

1. A spatially matching object without an obvious label;
2. A spatially mismatching object without an obvious label;
3. A random, unrelated object.









Abstract Match: <i>the flep in the afternoon</i>		Abstract Mismatch: <i>the flep on the afternoon</i>	
No Picture		No Picture	
Object Mismatch, Space Match		Object Mismatch, Space Match	
Object Mismatch, Space Mismatch		Object Mismatch, Space Mismatch	
Object Mismatch		Object Mismatch	

Figure 3.5: Example items for the abstract phrases *the flep in the afternoon* and *the flep on the afternoon*

The three photographs shown before the conjunction phrases that acted as non-spatial matches for the concrete preposition phrases (e.g., *and the plate*) consisted of:

1. An *in* version of the object in the phrase;
2. An *on* version of the object in the phrase;
3. A random, unrelated object.

The three photographs shown before the conjunction phrases that acted as filler/control phrases for the study (e.g., *and the string*) consisted of:

1. One version of the object in the phrase;

2. Another version of the object in the phrase;
3. A random, unrelated object.

Figure 3.6 shows example photographs for the conjunction match phrase *the flep and the plate* and the conjunction filler/control phrase *the flep and the guitar*.









Control: <i>the flep and the plate</i>		Filler: <i>the flep and the guitar</i>	
No Picture		No Picture	
Object Match 1: <i>In Version</i>		Object Match 1	
Object Match 2: <i>On Version</i>		Object Match 2	
Object Mismatch		Object Mismatch	

Figure 3.6: Example items for concrete conjunction phrases

### 3.5 Task questions

For a random set of 25% of the items, participants were prompted to answer yes/no questions about the phrase. These questions were included in order to ensure that participants read all of the phrases and attended to the experiment. The task questions required participants to recall the words in the preceding phrase. The questions did not ask participants to make semantic/grammatical judgments about the phrases. The questions did not require participants to recall any aspect of the photographs presented before the phrases, nor to make any judgment about them.

The questions all began with the prompt *Was there a ... ?* For each concrete phrase, the question to which "yes" was correct simply repeated the phrase after the prompt, beginning from the nonce, located noun. For example, for the phrase *The flep in the bowl*, the question to which "yes" was correct was *Was there a flep in the bowl?* Questions for which "no" was the correct response were designed by changing the preposition or the conjunction in the phrase, and/or by changing the phrase's reference noun. For instance, for *The flep in the bowl*, questions to which a "no" response was correct could contain a different conjunction or preposition (i.e., *Was there a flep on the bowl?*), a different reference noun (e.g., *Was there a flep in the bucket?*), or both a different conjunction/preposition and a different reference noun (e.g., *Was there a flep on the bucket?*).

Since locative questions about abstract concepts are semantically infelicitous (e.g., *#Was there a flep on the whole?*), questions for abstract phrases only manipulated the nonce, located noun. For instance, for *The flep on the whole*, the question created to which "yes" was correct was *Was there a flep?* (versus *Was there a toose?*).

### **3.6 Presentation**

At the beginning of each trial, a fixation cross was displayed for 750ms on the computer monitor, and then either a photograph or a blank, white screen (in the "no picture" condition) was presented for 500ms. During the "no picture" trials,

a 500ms auditory tone (Described in Section 3.3.4) was played, simultaneous to the presentation of the blank, white screen. After the tone + blank screen or photograph ended, a fixation cross was presented for 1000ms. Then the phrase began, with each word presented in black 60 pt. Dotum font in the center of a white screen. Only the first letter of the first word of each phrase (i.e., "The") was capitalized; the subsequent words were presented in all lower-case letters. Each non-final word of the phrase was displayed on the screen for 500ms. The final word (reference noun) was presented for 1250ms. See Figure 3.7 for a visual depiction of presentation timing.


Inter-item interval	Picture/ Tone	Inter-stimulus interval	The1	Nonce Noun	Prep/ Conj	The2	Reference Noun
+		+	The	flep	in	the	plate
1500ms	500ms	1000ms	500ms	500ms	500ms	500ms	1250ms
← 4750ms →							
← 6250ms →							

Figure 3.7: Timing of presentation of 75% of no items with no response task

For 25% of trials (144 trials for each participant), a task question was presented after the phrase finished (See Section 3.5 for a description of the task). The question was displayed in centered, 48 pt., white text in Dotum font on a black screen. The question remained on the screen for 3000ms or until the participant indicated his/her response by pressing the respective button on a five-button Serial Response Box (SRBox). Responses were recorded by E-Prime software. After 3000ms or as soon as the participant had indicated his/her response, a 2200-millisecond feed-



back display was presented- either "Correct!" in blue lettering, "Incorrect" in red lettering, or "No Response Detected"<sup>3</sup> in pink lettering. After the feedback screen, a fixation cross was displayed for 750ms. Figure 3.8, below, depicts presentation timing when a task is included.


Inter-item interval	Picture/ Tone	Inter-stimulus interval	The1	Nonce Noun	Prep/ Conj	The2	Reference Noun	Question	Feedback
+		+	The	flep	in	the	plate	Was there a flep in the plate?	Correct!
1500ms	500ms	1000ms	500ms	500ms	500ms	500ms	1250ms	≤3000ms	2200ms
← 4750ms →								← ≤5200ms →	
← ≤11450ms →									

Figure 3.8: Timing of presentation of 25% of no items when a response task

### 3.7 Lists

As described earlier, 144 combinations of prepositions/conjunctions and reference nouns (spatial match, spatial mismatch, abstract match, abstract mismatch, conjunction match and conjunction control/filler) were used in this study (See Appendix B for the full list). There were four distinct possible stimuli shown before the phrases: three different photographs or an auditory tone presented alongside a blank, white screen. In total, this created 576 possible combinations of visual plus linguistic stimuli.

<sup>3</sup>"No Response Detected" was presented in the cases in which participants did not indicate a response within the 3000-millisecond time allotted for the button press. This only occurred for 11 trials across all 28 participants, i.e., for 0.3% of all of the questions given to all participants.

These 576 combinations were split into four different lists of 144 items. Within a single list, each phrase was presented once, preceded by one of the four possible visual/auditory stimuli. Each list presented items in different, pseudo-randomized orders. Phrase type was controlled for, so that two mismatch phrases were prevented from being presented subsequently. The list order also controlled for word type, so that the same reference noun was not repeated within eight consecutive items. These four lists were duplicated, with the orders of items pseudo-randomized, thus creating eight different lists of items, so that each phrase was repeated eight times, and so that each combination of phrase plus visual stimulus was doubled. Across these lists, each discrete combination of conjunction/preposition and reference noun (e.g. *and the bowl*) was presented with a different nonce noun (e.g., *the flep and the bowl*, *the toose and the bowl*), creating 1,152 unique phrases across the eight lists.

Each subject was presented with four of the eight lists (576 items). The four lists presented to a subject showed the same visual plus linguistic combination twice rather than presenting the subject with all four visual conditions for a single phrase. This was done so that no subject saw the same photograph before two different experimental phrases. So, for instance, if a subject was presented with a photograph of an upside-down bowl followed by the phrase *in the bowl*, s/he would not be presented with that photograph followed by the phrase *on the bowl*. Instead, s/he would be presented with the photograph of an upside-down bowl followed by *in the bowl* twice and never see that photograph before *on the bowl*. This decision- preventing participants from seeing identical photographs before differ-

ent experimental phrases- was made because it was postulated that participants might consciously compare connections between visual and linguistic stimuli if they were shown all four experimental conditions (e.g., *Is an upside-down bowl a better match for in the bowl or on the bowl?*). This type of conscious comparison was undesirable since the experimental objectives were to discover how visual information implicitly affects spatial-language processing.

### 3.8 Procedures

The experiment took place in a 9' x 10' sound-treated, electrically shielded room. During the experiment, participants were seated in a comfortable chair about one meter from a CRT computer monitor sitting on a table. Experimental stimuli were presented on this monitor using E-Prime software, version 2.0.8.90. The auditory tone was played at 55.5 dB SPL from diagonal left and right speakers (Realistic Minimus-7), which were each placed approximately one meter from the participant. During the experiment, participants were alone in the sound-treated room. A video camera filmed (but did not record) the participant as s/he sat in the room, with the feed from the camera displayed on a television monitor outside the room, so that the experimenter could observe the participant during the experiment and so that the participant could alert the experimenter if s/he needed a break during the four experimental blocks (lists).

A table was placed over the participant's lap, and the five-button SRBox was set

on top of this table. Participants were asked to rest their left and right index fingers over the left-most and right-most buttons of the response box. Responses were indicated by pressing these two buttons- one button to indicate "yes" and one button to indicate "no". To correct for a possible left-versus-right-hand bias, the button coding for the SRBox was reversed for half of the participants, so that half of them indicated a "yes" response with their left index finger (the left-most button on the SRBox) and half with their right (the right-most button on the SRBox).

Before beginning the experimental lists, the experimenter described the procedures -telling participants that s/he would see pictures or hear a tone and then would read a phrase- and explained the response task. Then subjects were presented with six practice items followed by questions. None of the practice items were included as experimental items (see Table B.1 in Appendix B for a list of all items, including practice). Participants received feedback after each question (just as they would during the experiment). If participants answered most of these questions incorrectly (4 out of 6), or struggled to press the SRBox button within the 3000-millisecond time limit provided for responses, the experimenter would re-explain the procedures and restart the practice session. After this, and before initiating the experiment, the experimenter would answer any of the participant's remaining questions.

During the experiment, as described in Section 3.7, each participant was presented with four of the eight lists. List selection alternated between participants, so that every other participant was presented with the same set of four lists. To lessen

presentation-order effects, after half of the subjects had participated (i.e., after fifteen subjects), the presentation order of all of the lists was reversed<sup>4</sup>. Each block of 144 items lasted about eighteen minutes. Between each block, participants were given a five-to-ten minute break to stretch, drink water, etc., as the experimenter readjusted the electrode net and lowered the impedance of any electrode (by re-wetting or by re-positioning it) whose impedance measure had risen above 60 k $\omega$ .

### 3.8.1 EEG procedures

An EGI net with 129 electrodes was used for recording. The electrodes were each covered by a sponge, which was soaked in a saline solution for five minutes before use. The vertex (Cz) served as the reference during data collection. Once the net was fitted comfortably to the head, manual adjustments ensured that each electrode was positioned correctly on the scalp, with the reference electrode at its appropriate x-/y- position, equidistant from the top of both ears, and at the mid-line position between the tip of the nose and the base of the scalp at the back of the head. Impedance levels were lowered to 60 k $\Omega$ <sup>5</sup> before the beginning the experiment and were maintained at below 60 k $\Omega$  throughout the experiment. Vertical

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<sup>4</sup>Because of this, half of the participants saw the same items, and a quarter of the participants saw the same items presented in the same order.

<sup>5</sup>For most participants, it was impossible to get impedance levels below 60 k $\Omega$  for all electrodes due to the electrodes themselves being damaged or loose or due to impedances caused by oils in the scalp and/or in the hair. In these cases, the experimenter established acceptable impedance levels in electrodes in regions of interest- areas of the net which were to be subjected to analysis- and made a note of the remaining electrodes that had higher impedance.

and horizontal eye movements were measured by electrodes placed above and below the eyes and on the cheekbones. On-line EEG recordings were amplified with a band-pass filter of .01 to 100Hz, using Geodesic Amplifiers. A Geodesic software system (NetStation, Version 3.0) was used to collect data at a sampling rate of 250Hz per channel. During EEG recording, the experimenter monitored on-line EEG activity at all 129 channels, examining it for artifacts from electrical interference, unsatisfactory electrode placement, or excessive movement.

### **3.8.2 EEG data processing**

The continuous EEG was processed off-line. It was digitally filtered with a low-pass filter set at 20Hz in NetStation 4.0. A digital high-pass or band-pass filter was not utilized, maintaining the initial high-pass filtering level set for recording (0.01 Hz) so as to preserve slow cortical potentials (Grent et al. 2011). In BESA 5.3, artifacts from eye movements and eye blinks were corrected using an adaptive artifact correction tool that automatically applied a predefined source model to the data in order to identify EOG activity, including horizontal and vertical eye movements and eye blinks. Individual electrodes with high artifact were selected and their activity was replaced by spherical spline interpolation, which replaced the activity recorded in those channels with an estimation based on the measurements from nearby sites. Data was re-referenced to the average.

Two segments of EEG activity were used for analysis: 1) A segment beginning at the onset of the preposition or conjunction; 2) A segment beginning at the onset

of the reference noun<sup>6</sup>. Both epochs began 300ms before the onset of the stimulus, with a 200ms pre-stimulus baseline. The segments beginning with prepositions/conjunctions ended 2000ms post-stimulus onset, 500ms after the onset of the reference noun. The segments beginning with nouns ended 1500ms post-stimulus onset, 250ms after the noun disappeared from the screen.

Preposition and noun segments were compiled and averaged together based on the type of phrase within which they occurred and based on the type of visual stimuli preceding the phrase, for example, concrete spatial match phrase with no picture shown beforehand, abstract mismatch phrase with a spatially matching picture shown beforehand, et cetera. Segments containing activity exceeding  $\pm 120\mu V$  or with differential amplitudes exceeding  $75\mu V$  were rejected (marked as "bad" segments) and were not included in the averages<sup>7</sup>. For all participants, at least 60% of the segments for all conditions (e.g., concrete spatial match phrase with no picture shown beforehand) were required to be marked as "good" in order to make averages and to be included in the following analysis<sup>8</sup>.

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<sup>6</sup>ERP responses from the onset of the photographs were also recorded and segmented. Future analyses will include these segments.

<sup>7</sup>After artifact correction, facial channels were manually marked "bad" and were also excluded from averaging, since they contained a lot of noise for most participants and because activity from these channels was not of theoretical interest.

<sup>8</sup>Because of this requirement, the data from three of the original 33 participants were excluded from analysis.

### 3.8.3 Response task analysis

Associations between response task accuracy and stimuli type were assessed using logistic mixed effects regression, with accuracy as the binary (Correct or Incorrect) outcome variable and with the six phrase types (Abstract Match, Abstract Mismatch, Conjunction Control, Conjunction Match, Space Match, and Space Mismatch) and three picture types (No picture, Object or Space Match, Random Object) used as categorical predictor variables.

The distribution of the six specific picture types (No Picture, Object Match/Space Match, Object Match/Space Mismatch, Object Mismatch/Space Match, Object Mismatch/Space Mismatch, and Random Object) was such that there were disparate picture type variables per phrase type. For example, Object Mismatch/Space Match pictures were those that depicted nonce objects with spatial properties that matched the preposition in the phrase. These pictures were only shown before abstract match and mismatch phrases. The opposite was true for Object Match/Space Match pictures– these photographs were only presented before concrete match and concrete mismatch phrases. Because of this, the six picture types were collapsed into three types.

Participant IDs and item order (e.g., first, second, one-hundred-eleventh) were included as random intercepts.

All data were analyzed in R-Studio Version 0.98.501, using the Generalized Lin-



ear Mixed-Effects<sup>9</sup> function, called "glmer", from the lme4 package (Bates et al. 2015a,b).

### 3.8.4 EEG analysis

#### 3.8.4.1 Epochs

For each of the experimental items (space match/space mismatch and abstract match/abstract mismatch) and their matches (conjunction match- the non-spatial match for the space match/space mismatch phrases)<sup>10</sup>, an 1800-millisecond-long epoch was created for the reference noun. The epoch began 300ms before the onset of the reference noun, with a 200ms pre-stimulus baseline, and continued for 1500ms after the presentation of the reference noun. These epochs were averaged together, based on condition: noun type and preceding visual stimulus type, resulting in twenty 1800-millisecond-long averaged segments for each participant. See Table B.2 in Appendix B for the complete list of segment types for reference nouns. The averages for concrete reference nouns included nouns from the concrete conjunction, concrete spatial match and concrete spatial mismatch phrases for all picture conditions (Conditions 1-12 in Table B.2 in Appendix B). Averages for abstract reference nouns included nouns from the abstract match and abstract

<sup>9</sup>Family="binomial" for logistic regression.

<sup>10</sup>Filler/control conjunction phrases (e.g., *and the banana*) were excluded from all ERP analyses, since each of their reference nouns was not a match for any of the experimental nouns, nor were any experimental pictures (spatial match and spatial mismatch) shown before these phrases. Future analyses will explore ERP responses to these phrases.

mismatch phrases for all picture conditions (Conditions 13-20 in Table B.2 in Appendix B). For noun segments, the epoch used to perform analyses was 1250 milliseconds long (from 0-1250ms post-stimulus-onset), since this represented the time period that the nouns were displayed on the computer screen.

For all of the concrete phrases (space match/mismatch and conjunction match), an 1800-millisecond-long epoch was also created from the onset of the preposition or conjunction. The epoch began 300ms before the onset of the preposition, with a 200ms pre-stimulus baseline, and continued for 1500ms after the presentation of the preposition. This epoch included the display of the following definite determiner, *the*, which began 500 milliseconds after the onset of the preposition. The epoch also included the presentation of the reference noun, which was displayed another 500 milliseconds later, i.e., 1000 milliseconds after the onset of the preposition (and 500 milliseconds after the preposition's offset). These epochs were averaged together, based on condition: preposition/conjunction and preceding visual stimulus type, which resulted in eight 1800-millisecond-long averaged segments for each participant. See Table B.3 in Appendix B for the complete list of segment types for prepositions/conjunctions. For preposition/conjunction segments, the epoch used for analysis was 1000 milliseconds long (from 0-1000ms post-preposition-onset), since this represented the time period before the nouns appeared on the screen, i.e., when the preposition and the following determiner were displayed. Since the point at which a phrase is revealed to be a spatial match or mismatch is at the onset of the reference noun, preposition conditions (Conditions 1-4 in Table B.3 in Appendix B) averaged across the spatial match and

mismatch conditions (Conditions 5-12) in Table B.2.

### **3.8.4.2 Selection of temporal/spatial regions of interest**

In IGOR Pro Version 6.43a (WaveMetrics, Inc., Portland, OR, USA), averaged epochs for all picture conditions within a word-type (concrete nouns, abstract nouns, concrete prepositions/conjunctions) for all subjects were used to plot Global Field Power (GFP), in order to find time windows of interest (time windows with relatively high variance) within the ERP epoch, under the assumption that time windows with high variance represented bands of time in which there was relatively more electrophysiological activity (i.e. peaks) across all conditions and across all subjects (Lehmann and Skrandies 1980).

Because variance tended to increase with time (across the recording epoch), it was generally the case that early, obligatory peaks were more evident in a GFP analysis than later peaks, which were occluded by increasingly high variance. When the GFP analysis did not yield clear peaks, a temporal Principal Components Analysis (PCA) was used to extract factors/components that represented  $\geq 95\%$  of the variance, where a factor score was provided for each time point (every 4 milliseconds, with a sampling rate of 250Hz) for each component in IGOR Pro. Components represented the variance for each time point around the grand mean across all sites, participants, and conditions. The full epoch (excluding pre-stimulus activity) was submitted to the temporal PCA using the covariance matrix, so that the variables were the time points within an epoch and the observations for each vari-

able were the participants (28) multiplied by the number of conditions multiplied by the number of sites (125<sup>11</sup>). After factor extraction, components were rotated in order to achieve simple structure using a Varimax criterion rotation function in IGOR Pro (Kayser 1959). In each of these rotated components, adjacent, co-varying time-points that had relatively high factor scores were considered representative of ERP deflections where voltage co-varied. These adjacent time-points were identified as temporal regions of interest and were used for analysis.

Temporal regions of interest were then used as epochs upon which a spatial PCA was performed, in order to extract components that represented  $\geq 95\%$  of the variance. For the spatial PCA, the variables were 125 electrodes, and the observations were the time points within each temporal region of interest multiplied by the number of participants (28) and the number of conditions. The number of conditions depended on which segments were being analyzed. For concrete reference nouns, there were 12 conditions; the nouns occurred in three phrase types (following *in*, *on*, or *and*) and were preceded by four different types of visual stimuli. For abstract reference nouns, there were 8 conditions, since abstract reference nouns never followed the conjunction *and*. For prepositions/conjunctions, there were 12 conditions: Whether the phrase began with *in*, *on* or *and* multiplied by the four preceding picture types. In the spatial PCA analysis, factor scores were provided for each electrode for each component. The factor loadings from the components that accumulated at least 95% of the variance were again rotated using a Varimax

<sup>11</sup>The four facial electrodes (sites 125, 126, 127, and 128) were excluded from analysis. See Section 3.8.2

rotation to achieve a simpler structure, and these rotated components were used to select electrodes that co-varied, under the assumption that electrodes that co-vary represent spatial regions where electrophysiological activity is similar. Following the methods used in Noordzij et al. (2006) and Mecklinger and Pfeifer (1996), these sets of electrodes were pooled and averaged to create topographical regions (F7, Fz, Cz, O1, etc.), which were then categorized for Hemisphere (left, medial, right) and Anteriority (frontal, central, posterior).

#### **3.8.4.3 Statistical analysis**

Data were down-sampled and time averaged in IGOR Pro, so that data points represented activity from 40-millisecond intervals (approximating data recorded at a sampling rate of 25Hz, rather than 250Hz). In R-Studio Version 0.98.501, down-sampled data from the onset of concrete reference nouns, abstract reference nouns, and concrete conjunctions/prepositions were averaged across time windows of interest and electrode-site regions of interest (identified by the temporal or spatial PCA, respectively). Spatial regions were categorized for anteriority (frontal, central, posterior) and hemisphere (left, medial, right). Averaged activity for each time window of interest was subjected to a repeated-measures (within participant) ANOVA of voltage with the factors word/phrase type, picture type, anteriority and hemisphere with a critical  $p$  value of 0.05. All comparisons included the Hemisphere and Anteriority as factors, but the word/picture variables used as factors in the analyses varied depending on the segment type.

For concrete reference noun segments, ANOVAs included the following factors: 1) Phrase type (Spatial, headed by a preposition and Non-spatial, headed by a conjunction); 2) Reference Noun type (Spatial match, Spatial mismatch, Conjunction match); 3) Object in Picture (No Object, Matching Object and Mismatching object); 4) Anteriority (Frontal, Central, Posterior); 5) Hemisphere (Left, Right, Medial). A secondary set of ANOVAs was calculated for just the nouns presented in spatial phrases (i.e., after prepositions) when spatially matching or mismatching pictures were shown before the phrases. In this case, the factors were: 1) Space of Reference Noun (whether it matched the preceding preposition); 2) Space of Picture (whether the configuration of the object displayed matched the preposition); 3) Anteriority (Frontal, Central, Posterior); 4) Hemisphere (Left, Right, Medial).

For abstract reference noun segments, ANOVAs included the following factors: 1) Reference noun type (Abstract match, Abstract mismatch); 2) Picture type (No Object, Spatially matching object, Spatially mismatching object, Random object); 3) Anteriority (Frontal, Central, Posterior); 4) Hemisphere (Left, Right, Medial). A secondary set of ANOVAs was calculated for just the items when spatially matching or mismatching pictures were shown before the phrases. For this analysis, the factors were: 1) Reference noun type (Abstract match, Abstract mismatch); 2) Space of Picture (whether the configuration of the object displayed matched the preposition); 3) Anteriority (Frontal, Central, Posterior); 4) Hemisphere (Left, Right, Medial).

For preposition and conjunction segments, ANOVAs included the following factors: 1) Phrase type (Spatial, headed by a preposition, Non-spatial, headed by a conjunction); 2) Object in Picture (No Object, Object Matching Upcoming Noun, and Object Not Matching Upcoming Noun); 3) Anteriority (Frontal, Central, Posterior); 4) Hemisphere (Left, Right, Medial). A secondary set of ANOVAs was calculated for just the preposition phrases. For these comparisons, the factors were: 1) Picture type (No Picture, Spatially matching, Spatially mismatching, Random object); 2) Anteriority (Frontal, Central, Posterior); 3) Hemisphere (Left, Right, Medial). And a final set of ANOVAs was calculated for just the prepositional phrases when spatially matching/mismatching pictures were displayed. In this case, the factors were: 1) Space in Picture (Spatially matching, Spatially mismatching) 2) Anteriority (Frontal, Central, Posterior); 3) Hemisphere (Left, Right, Medial).

A Huynh-Feldt correction was applied to all tests with factors of two or more levels (e.g., Reference noun type: spatial match, spatial mismatch and conjunction match) to correct for possible violations to assumptions of sphericity (Huynh and Feldt 1976, Noordzij et al. 2006). All analyses were calculated using the ezANOVA function from the 'ez' package installed in R-Studio v. 0.98.501 (Lawrence 2013).

For the sake of parsimony, only significant effects involving factors of theoretical interest (picture type, phrase type, and interactions between these factors and/or hemisphere and/or anteriority) are presented in the following chapter. Significant

effects involving only hemisphere and/or anteriority are not discussed.



# Chapter 4

## Results

*This chapter describes the results of the response task and the ERP experiment. Response task accuracy measures adhered to predicted patterns. ERPs to phrase/word type also conformed to predictions for concrete phrases. A sustained occipital negativity was evident during the processing of prepositional phrases as compared to conjunction phrases, and N400 responses significantly increased when nouns mismatched the preceding preposition. ERPs to mismatched abstract nouns did not show a significant N400 effect, and instead showed a late central positivity beginning 700ms after the onset of the noun. The influence of picture type significantly affected ERPs to concrete phrases, but these effects diverged from predictions. For prepositions, there was no significant N400 effect found to prepositions whose spatial semantics mismatched the preceding picture. Instead, spatially mismatching pictures yielded a fronto-central, left-lateralized negativity beginning 600ms after the onset of the preposition (when the preposition was no longer on the screen). For concrete nouns, the spatial configuration of the object in the preceding pictures was reflected in a frontal negativity to the noun, which was larger when the picture was spatially mismatching. This frontal negativity was followed by a sustained occipital positivity, and showed an interaction between phrase type and picture type, where the negativity to matched nouns after spatially mismatching pictures was more broadly distributed than the negativity to matched nouns after spatially mismatching pictures.*

## 4.1 Results of behavioral task

In general, participants performed very well on the response task, with a mean accuracy at about 92% a median of 93%, and a range of accuracy scores from 78% correct<sup>1</sup> to 98% correct, with a standard deviation of 5.4% correct. There was a total of 11 trials (across the response data from all 28 participants) for which neither a "yes" or "no" response was recorded. These 11 trials were excluded from analysis. See Figure 4.1 for response accuracy across all items.

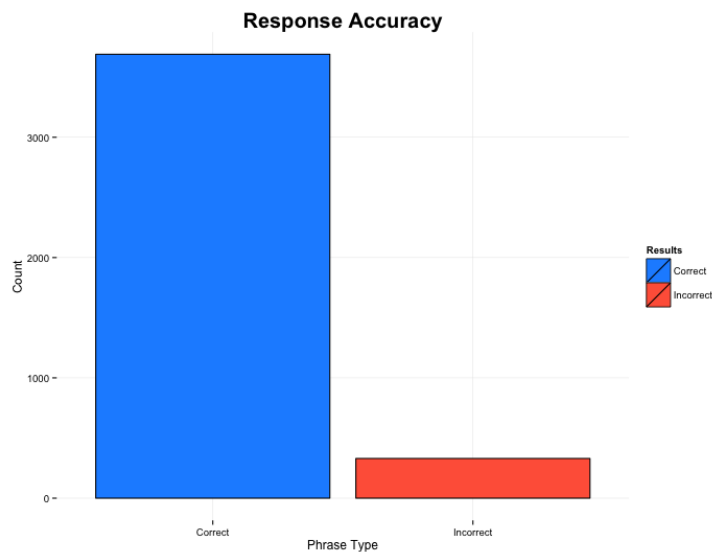


Figure 4.1: Response accuracy overall (for all questions answered by all participants).

<sup>1</sup>The lower-end score of this range is surprisingly low, and is a full four percentage points lower than the next lowest accuracy score (82%). The participant who scored 78% was confused about an aspect of the task for the first block of the experiment, thinking that it was necessary to base the answer to each question on all of the preceding phrases, rather than merely on the immediately preceding phrase (e.g., *Was there a flop in the bowl?*  $\approx$  *Was there [ever] a flop in the bowl [in any of the phrases you have read thus far]?*).

The data from the response task were analyzed using logistic mixed effects regression (see Section 3.8.3 for details). It was found that the best model for predicting response accuracy included phrase type (Abstract Match, Abstract Mismatch, Conjunction Control, Conjunction Match, Space Match, Space Mismatch) as the predictor variable with participant ID and item order as random intercepts. This model was found to be a significantly better fit for accuracy proportions (Correct:Incorrect) as compared to a model including only the random intercepts- participant ID or item order, or both participant ID and item order,  $p < 2.2e^{-16}$  for all three comparisons. It was also a better fit than any model containing picture type as a fixed effect, ( $p < 6.18 e^{-14}$  for the model with picture type as the fixed effect and both participant ID and item order as random intercepts).

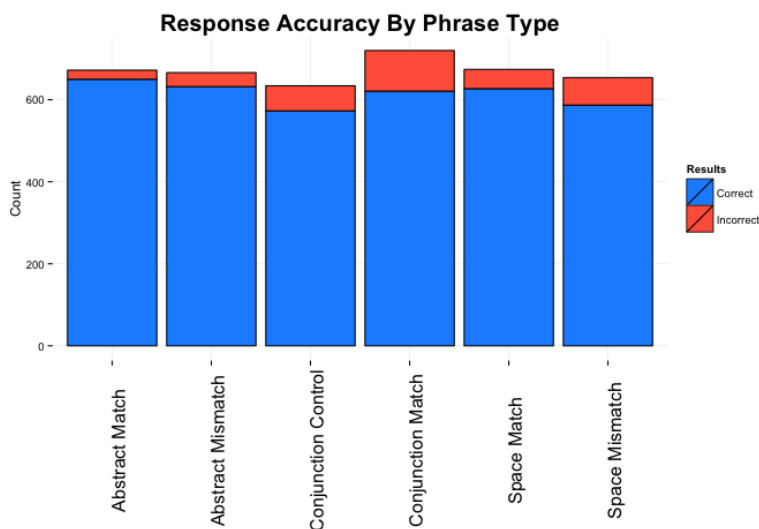


Figure 4.2: Response accuracy for each phrase type.

In general, participants performed best on the questions about the abstract match

and mismatch phrases than about any other phrase type. They incorrectly answered an average of approximately 3% and 5% of the questions following abstract match and mismatch phrases, respectively. They performed worse on the questions following conjunction match phrases (*and the bowl*) and conjunction control phrases (*and the banana*) than they did after every other phrase type, incorrectly answering an average of approximately 10% and 14% of them, respectively. The rates for incorrectly answering questions after spatial match and mismatch phrases was in the middle, at about 7% and 10%, respectively. See Table 4.1 and Figure 4.2<sup>2</sup>.

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<sup>2</sup>In Figure 4.2, bars represent raw count of question/answer type. These totals are slightly different for each phrase type, since questions were randomly presented after 25% of all trials for each subject (i.e., It was not specified that questions would be presented after a certain percentage of each type of phrase) by E-Prime software. Since the logistic regression analysis compares proportions of responses (Correct : Incorrect) within each phrase type, differing total counts do not devalue the strength of the significance tests.

		PHRASE TYPE						
		Concrete Conjunction Match	Concrete Conjunction Control	Concrete Spatial Match	Concrete Spatial Mismatch	Abstract Spatial Match	Abstract Spatial Mismatch	Total
CORRECT	Count	573	621	627	587	650	632	3690
	Row Percent	15.5%	16.8%	17.0%	15.9%	17.6%	17.1%	91.8%
	Std Residual	0.37	1.55	0.34	0.54	1.34	0.84	-
INCORRECT	Count	61	99	47	67	22	34	330
	Row Percent	18.5%	30.0%	14.2%	20.3%	6.7%	10.3%	8.2%
	Std Residual	1.24	5.12	1.12	1.81	4.47	2.80	-
Column Total		634	720	674	654	672	666	4020

Table 4.1: Contingency table for response task accuracy by different phrase types.

For the logistic regression analysis, accuracy counts for abstract match phrases were used as the intercept (the default value of the factor). For each of these phrases (and for abstract mismatch phrases), the question following only focused on the nonce, located object from the phrase, (e.g., PHRASE: *The floop in the wrong*, QUESTION: *Was there a stook?*). These questions were predicted to be less taxing than the questions that included the preposition/conjunction and reference noun, and consequently were predicted to yield the lowest proportion of incorrect responses. Further, it was predicted that participants would more accu-

rately answer questions after match phrases than after mismatch ones. Therefore, abstract match phrases were predicted to elicit the highest proportion of correct responses out of all the phrase types, and could provide a low baseline for comparative proportions of incorrect responses.

	OR	97.5% C.I.
FIXED EFFECT: PHRASE TYPE		
Intercept (Abstract Match)	0.0183	(0.0102, 0.0312)
Abstract Mismatch	1.6726	(0.9286, 3.0700)
Conjunction Control	3.5844	(2.0834, 6.3727)
Conjunction Match	6.0741	(3.6137, 10.6436)
Space Match	2.3428	(1.3331, 4.2314)
Space Mismatch	3.9190	(2.2808, 6.9668)

Table 4.2: Odds ratios and 97.5% confidence intervals for the odds of answering a question incorrectly compared to the intercept- abstract match phrases- with a random intercept for Participant ID and Item Order.

The odds of participants' missing a question for abstract match phrases were very low (0.02, 97.5% C.I. [0.01, 0.03]). Participants were about 1.7 times more likely to miss questions after abstract mismatch phrases than after the abstract match ones. This effect was only marginally significant,  $p \approx 0.09$ , 97.5% C.I. (0.93, 3.07). The odds of missing a question after a conjunction control or a conjunction match was about 3.6 and 6.0 times more likely than missing a question after an abstract match phrase,  $p \approx 7.02e^{-06}$  (97.5% C.I [2.08, 6.37]) and  $p \approx 7.06e^{-11}$  (97.5% C.I [3.61, 10.64]), respectively. Participants were about 2.3 times more likely to answer a question incorrectly after a space match phrase than after an abstract match phrase,  $p \approx .003$  (97.5% C.I [1.33, 4.23]), and 3.9 times more likely to miss a question after a spatial mismatch phrase than after an abstract

match phrase,  $p \approx 1.48e^{-6}$  (97.5% C.I [2.28, 7.0]).

Based on the overall averages, see Figure 4.1, behavioral results show that participants were successful at recalling the words in the phrases they read, suggesting that they were reading the phrases, paying attention to them, and holding the words in working memory.

## **4.2 ERP results for reference nouns**

### **4.2.1 Concrete reference nouns**

From the GFP plot, an early peak from 152 to 300 milliseconds was identified. Later peaks were occluded by increasingly high variance, so the data from 0 to 1250 milliseconds post-stimulus onset was then submitted to a temporal Principle Components Analysis (PCA) in order to identify later time-windows within which time-points shared variance. This temporal PCA yielded four additional time regions of interest: 324-460ms, 500-652ms, 780-1040ms, and 1052-1248ms. These time regions of interest were used to perform an exploratory spatial PCA in order to select electrode groupings within which the activity recorded at individual electrodes in the group co-varied. The rotated components identified eleven sets of electrode sites that co-varied across the five time regions of interest. These eleven regions were selected as spatial regions of interest for all five time win-

dows<sup>3</sup>. Matching numbers of electrodes in all left/right regions (e.g., F7 and F8) were selected. Figure 4.3 displays the eleven regions selected. These eleven regions were: left frontal including F7, central frontal including Fz, right frontal including F8, left central including C3, central including Cz, right central including C4, left posterior including P7, central posterior including Pz, right posterior including P8, left occipital under O1, and right/central occipital under O2. For the sake of parsimony, regions are identified and referred to by the nearest or included 10-10 electrode site (e.g., F7, Fz, O2).

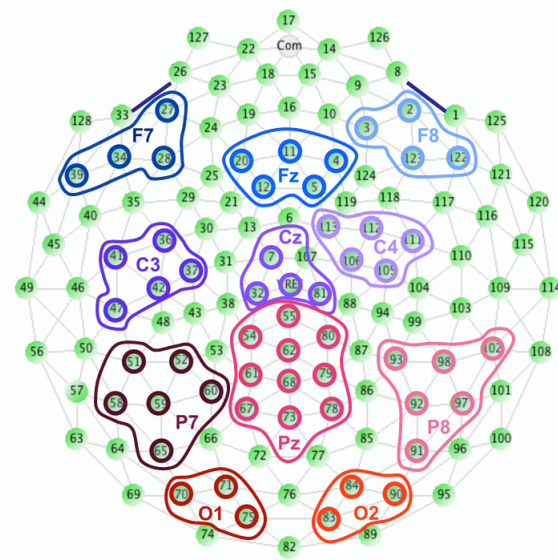


Figure 4.3: Eleven regions selected from rotated components from five time windows. These regions were categorized by anteriority (frontal, central, posterior) and hemisphere (left, right, central) for analysis.

<sup>3</sup>Although some electrodes on the periphery of the net often contributed to the variance of different components, these electrodes were excluded from analysis since they tended to be noisy for many participants and because their activity was often spline interpolated to nearby electrodes in order to keep their activity within artifact-detection thresholds ( $\pm 120\mu V$ ).



These 11 regions were then categorized for laterality/hemisphere and anteriority. Frontal regions were F7, Fz, and F8. Central regions were C3, Cz and C4. Posterior regions were P7, Pz, P8, O1 and O2. Left regions were F7, C3, P7 and O1. Medial regions were Fz, Cz and Pz. Right regions were F8, C4, P8, and O2.

Data from -300 milliseconds before the onset of the visual presentation nouns to 1250 ms post-noun onset were down-sampled in IGOR Pro, so that each data-point represented activity from 40-millisecond intervals (to a sampling rate of 25Hz). The time-averaged data were imported into R-Studio and were further averaged into five time windows corresponding to those identified by the GFP analysis and the temporal PCA: 180-300ms, 340-460ms, 500-620ms, 780-1020ms, and 1060-1220ms. In R-Studio, averaged voltage across these time intervals of interest was subjected to repeated-measure ANOVAs by participant with the dependent factors: Reference Object Type (conjunction match, spatial match, spatial mismatch), or Phrase Type (preposition or conjunction), Picture Type (No Picture, Matching Object, Mismatching Object), Anteriority (frontal, central, posterior), and Hemisphere (left, right, medial). A secondary set of ANOVAs was calculated for just the nouns presented in spatial phrases (i.e., after prepositions) when spatially matching or mismatching pictures were shown before the phrases. In this case, the factors were: 1) Space of Reference Noun (whether it matched the preceding preposition); 2) Space of Picture (whether the configuration of the object displayed matched the preposition); 3) Anteriority (frontal, central, posterior); 4) Hemisphere (left, right, medial). Mauchly's sphericity tests were conducted on all comparisons of factors with two or more levels (Reference noun

type, Hemisphere, Anteriority) and interactions between factors (when there was greater than one degree of freedom in the numerator), and a Huynh-Feldt correction was applied in order to correct for possible violations to assumptions of sphericity (Huynh and Feldt 1976). The critical  $p$  value was 0.05. In Table 4.3, all significant ( $p \leq 0.05$ ) and marginally significant ( $p < 0.1$ ) effects are displayed. In the text, only effects with  $p \leq 0.07$  are discussed. The following sections only show responses for the time windows of analysis. For graphs of comparisons across the entire epoch (and for all 11 electrode regions), see Section D.2.1 in Appendix D.

TIME	EFFECT	F	$\epsilon$	p	
180-300ms	Phrase	F(1, 27)	3.30	N/A	0.080 .
	Phrase * Object in Picture * Anteriority	F(4, 108)	2.25	0.77	0.087 .
	Reference Noun	F(2, 54)	3.02	1.00	0.057 .
	Space of Reference Noun * Anteriority	F(2, 54)	2.80	0.94	0.073 .
340-460ms	Object in Picture	F(2, 54)	2.59	1.00	0.084 .
	Object in Picture * Hemisphere	F(4, 108)	2.37	0.91	0.063 .
	Reference Noun	F(2, 54)	3.77	0.96	0.031 *
	Space in Picture * Anteriority * Hemisphere	F(4, 108)	2.73	0.71	0.053 .
500-620ms	Phrase * Anteriority * Hemisphere	F(4, 108)	2.84	0.79	0.040 *
	Reference Noun	F(2, 54)	4.13	1.00	0.021 *
	Reference Noun * Object in Picture	F(4, 108)	2.03	1.00	0.095 .
	Reference Noun * Anteriority * Hemisphere	F(8, 216)	2.76	0.85	0.010 *
	Space of Reference Noun * Anteriority	F(2, 54)	2.76	0.95	0.075 .
	Space of Reference Noun * Hemisphere	F(2, 54)	2.52	0.99	0.091 .
	Space of Reference Noun * Space in Picture * Hemisphere	F(2, 54)	2.65	0.72	0.099 .
	Space in Picture * Anteriority * Hemisphere	F(4, 108)	2.36	0.84	0.069 .
780-1020ms	Phrase * Hemisphere	F(2, 54)	3.37	0.89	0.048 *
	Reference Noun	F(2, 54)	3.42	1.00	0.040 *
	Space of Reference Noun * Anteriority	F(2, 54)	3.62	0.78	0.046 *
1060-1220ms	Phrase * Hemisphere	F(2, 54)	3.59	0.95	0.037 *
	Reference Noun * Object in Picture	F(4, 108)	2.41	1.00	0.054 .
	Reference Noun * Object in Picture * Anteriority	F(8, 216)	1.93	0.78	0.075 .
	Space of Reference Noun * Space in Picture * Hemisphere	F(2, 54)	4.33	0.95	0.020 *

Table 4.3:  $F$ ,  $\epsilon$ , and  $p$  values for significant ( $p$  value under 0.05) or nearly significant ( $p$  value under 0.1) effects of repeated-measures ANOVAs by participant at the onset of concrete nouns within the five time windows of interest, after the Huynh-Feldt correction (when applicable, i.e., when factors had more than two levels).

For all time regions of interest, the main effect of Anteriority, Hemisphere, and/or the interaction of these two factors had a significant impact on voltage. However, because these effects do not include the factors relevant to the research questions or hypotheses for this experiment (i.e., picture and/or phrase type), they are not reported.

#### 4.2.1.1 140-300 milliseconds

Between 140 to 300 milliseconds, no main effect or interaction was statistically significant. The main effect of reference noun type (conjunction match, spatial match, spatial mismatch) had a marginally significant impact on voltage during this time window,  $F_{(2,54)} = 3.02$ ,  $p < 0.06$ ,  $\epsilon = 1$ , where responses were generally more negative for spatial mismatch nouns and conjunction match nouns than for spatial match nouns. Figure 4.4 shows averaged voltage by reference noun type (gray for conjunction match, blue for spatial match, red for spatial mismatch) across all electrode regions.

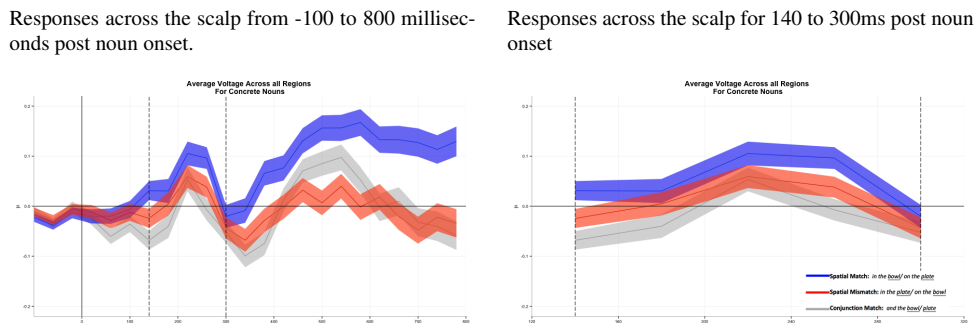


Figure 4.4: Responses to different reference noun types averaged across eleven spatial regions chosen from rotated components for the second time window of interest post-noun onset. Gray is conjunction match, blue is spatial match, red is spatial mismatch (see legend at bottom right). Dotted lines represent beginning and end of first epoch of interest (140 to 300ms post-noun onset).

In the above graph, and for all of the following line graphs of ERP activity, the x-axis depicts time in milliseconds (ms) and the y-axis depicts amplitude in microvolts ( $\mu V$ ):

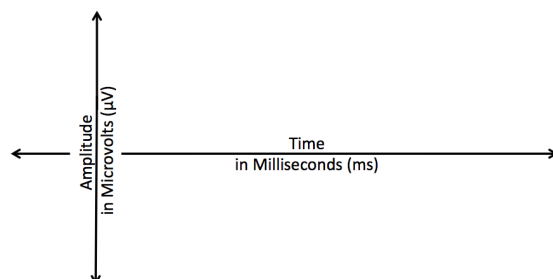
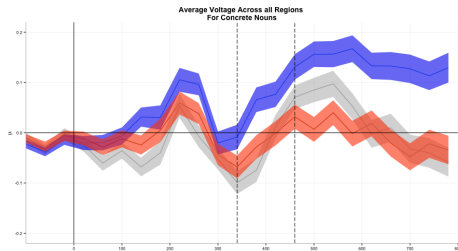


Figure D.13 in Appendix D displays responses to reference noun type at all 11 regions for this time window.

#### 4.2.1.2 340-460 milliseconds

In this time window, only the main effect of reference noun type (conjunction match, spatial match, spatial mismatch) made a significant impact on voltage,  $F_{(2,54)} = 3.77$ ,  $p < 0.05$ ,  $\epsilon > 0.95$ , where responses to spatial mismatch nouns and conjunction match nouns (*on the bowl*, and *the bowl*, respectively) were more negative than responses to spatial match nouns (*in the bowl* and conjunction match nouns). This relatively negativity was broadly distributed, but was greatest in medial regions. Compare red (spatial mismatch) and gray (conjunction match) waveforms to blue (spatial match) waveform in Figure 4.5b, which shows averaged responses across the scalp. Figure D.14 in Appendix D shows responses to the three different noun types for this time window for all 11 regions.

Responses across the scalp from -100 to 800 milliseconds post noun onset.



Responses across the scalp for 340 to 460ms post noun onset

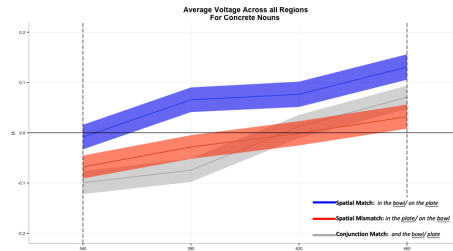


Figure 4.5: Responses to different reference noun types averaged across eleven spatial regions chosen from rotated components for the second time window of interest post-noun onset. Gray is conjunction match, blue is spatial match, red is spatial mismatch (see legend at bottom right). Dotted lines represent beginning and end of second epoch of interest (340 to 460ms post-noun onset).

The interaction between the type of object shown in the picture before the phrase (no picture, matching object, mismatching object) and hemisphere had a marginally significant effect on voltage during this time window,  $F(4,108) = 2.37, p < 0.07, \epsilon > 0.90$ . This result reflected more positive ERPs to nouns in medial regions (Fz, Cz, and Pz) after seeing a picture of a matching object, compared to responses after seeing a picture of a mismatched, unrelated object, or after seeing no picture at all. Figure 4.6 shows responses to all nouns after no seeing no picture (gray), a picture of a matching object (blue), and a picture of a mismatching, random object (red) across hemisphere levels (left, medial and right).

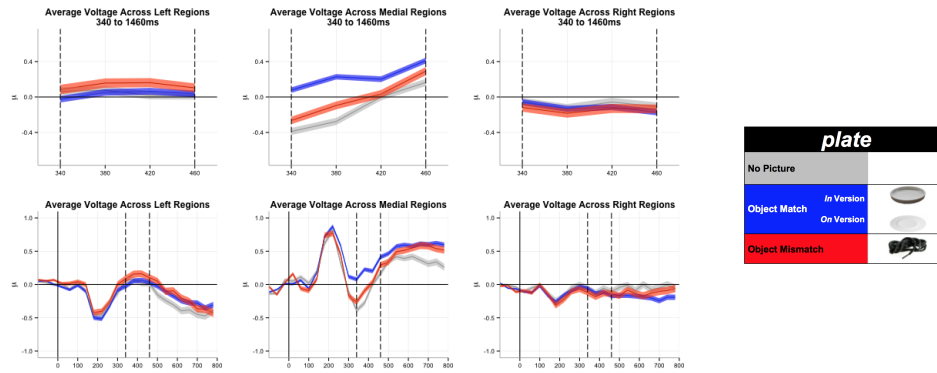


Figure 4.6: Responses averaged across hemisphere (left, right, central) chosen from rotated components for the second time window. Waveforms represent responses averaged across all nouns (conjunction match, spatial match and spatial mismatch) after no picture was shown (gray), after a matching object was shown (blue), and after a random, mismatching object was shown (red). See legend (right) for example pictures. Top row shows responses for just the second time window of interest. In bottom row, showing responses from -100 to 800ms post-noun onset, dotted lines represent beginning and end of second epoch of interest (340 to 460ms post-noun onset).

See Figure D.15 in Appendix D to see how object-in-picture type affects responses to nouns for this time window in all 11 regions used for analysis.

When comparisons were limited to the experimental, spatial nouns (after prepositions), a marginally significant interaction was discovered between the spatial configuration of the object depicted in the picture (spatially matched vs. spatially mismatched), anteriority, and hemisphere during this time window,  $F_{(4,108)} = 2.73$ ,  $p < 0.06$ ,  $\epsilon > 0.70$ . This effect reflected a difference between frontal versus posterior regions and between left/medial versus right regions.

Responses to nouns after spatially mismatching pictures were relatively more pos-

itive in posterior regions (P7, Pz, O1 and O2). This pattern was slightly lateralized, so that the difference between responses to spatial nouns after spatially matching versus mismatching pictures was greater in left posterior regions (P7 and O1) as compared to medial and right posterior regions (Pz and O1). Concurrent to this response, in left and medial frontal regions (F7 and Fz), the opposite effect was evident, so that responses to nouns after spatially mismatched pictures was more negative than responses to spatially matched pictures. Compare blue (after spatially matching pictures) and orange (after spatially mismatching pictures) lines in Figure 4.7.



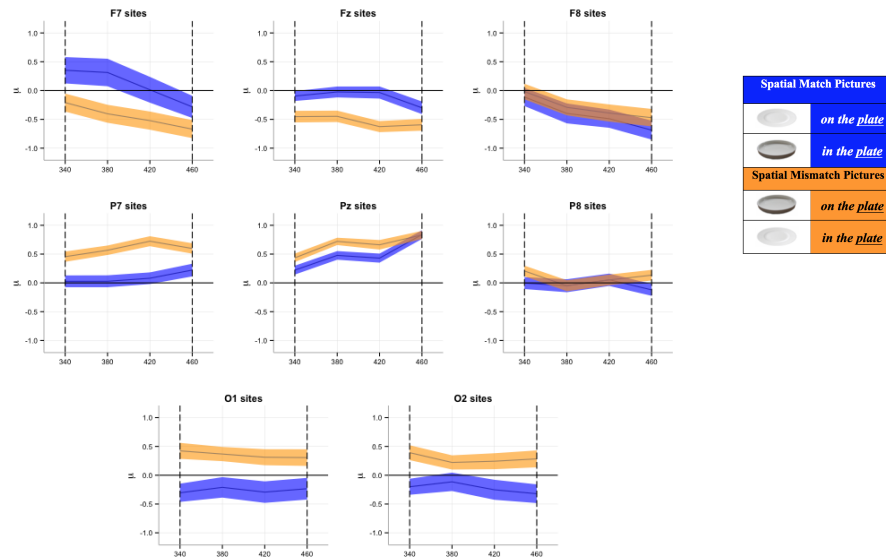


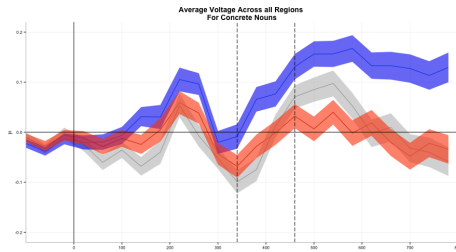
Figure 4.7: Responses at frontal and posterior regions for the second time window. For this figure, responses to concrete nouns in prepositional phrases are displayed for the two experimental picture conditions– when the spatial configuration of the picture matches the space of the preposition (e.g., a picture of a concave plate before "in the plate" or a picture of a flat plate before "on the plate") and when the spatial configuration of the picture does not match the space of the preposition (e.g., a picture of a concave plate before "on the plate" or a picture of a flat plate before "in the plate"). Dark blue waveforms are ERPs when the spatial configuration of the object matches the preposition in the phrase, orange waveforms are when the spatial configuration of the object is mismatched for the preposition in the phrase. Dotted lines represent beginning and end of second epoch of interest (340 to 460ms post-noun onset). See the legend (right) for example pictures for phrases containing the noun *plate*.

#### 4.2.1.3 500-620 milliseconds

During this time interval, the main effect of reference noun type (spatial match, spatial mismatch, conjunction match) made a significant impact on voltage,  $F_{(2,54)} = 4.13$ ,  $p < 0.05$ ,  $\epsilon = 1$ . In medial central and posterior sites (Cz and Pz), responses

to spatially matching nouns (*in the bowl*) continued to be more positive than responses to spatial mismatch nouns (*on the bowl*) and responses to conjunction match nouns (*and the bowl*). This topography was reflected by the significant interaction of reference noun type, hemisphere and anteriority, ( $F_{(8,216)} = 2.76$ ,  $p < 0.05$ ,  $\epsilon > 0.80$ ). See Figure 4.8 for averaged responses across all electrodes in the regions used for analysis.

Responses across the scalp from -100 to 800 milliseconds post noun onset.



Responses across the scalp for 500 to 620ms post noun onset

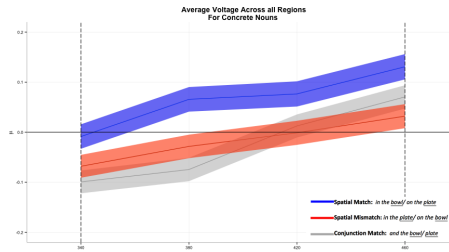


Figure 4.8: Responses to different reference noun types averaged across eleven spatial regions chosen from rotated components for the third time window of interest post-noun onset. Gray is conjunction match, blue is spatial match, red is spatial mismatch (see legend at bottom right). Dotted lines represent beginning and end of second epoch of interest (500 to 620ms post-noun onset).

See Figure D.16 in Appendix D for responses to the three reference noun types during this time window for each of the 11 regions used for analysis.

The three-way interaction between phrase type (spatial, headed by a preposition vs. non-spatial, headed by a conjunction), anteriority, and hemisphere was also significant in this time window,  $F_{(4,108)} = 2.84$ ,  $p < 0.05$ ,  $\epsilon > 0.75$ , reflecting a pattern whereby responses to nouns in spatial, prepositional phrases were more pos-

itive than responses to nouns in non-spatial, conjunction phrases in right frontal regions (F8), medial central regions (Cz), left and medial posterior regions (P7 and Pz), and were more negative in right and left posterior regions (P8, O1, and O2). See Figure D.17 in Appendix D for responses to prepositions and conjunction phrases during this time window for all 11 regions used in the analysis.

When only the experimental, spatial nouns (after prepositions) were included in the comparisons, the three-way interaction between the spatial configuration of the object displayed in the picture before the phrases (spatial match vs. spatial mismatch), anteriority, and hemisphere was found to be marginally significant in this time window,  $F_{(2,54)} = 2.65$ ,  $p < 0.07$ ,  $\epsilon > 0.80$ . Spatially matched pictures yielded more negative responses at noun onset in all right regions than spatially mismatched pictures did. This pattern also occurred in posterior left regions, but the inverse pattern (with more positive responses after spatially matched pictures) was observable in left frontal and central regions (F7 and C3). Compare blue (responses to nouns after spatially matching pictures) to orange (responses to nouns after spatially mismatching pictures) waveforms in Figure D.18 in Appendix D to see differences at all eleven regions during this time window.

#### 4.2.1.4 780-1020 milliseconds

During this time window, the main effect of reference noun type (spatial match, spatial mismatch, conjunction match) had a significant impact on voltage,  $F_{(2,54)} = 3.42$ ,  $p < 0.05$ ,  $\epsilon = 1$ . Responses to spatial match nouns (*in the bowl*) continued

(from the previous two time windows) to be more positive than responses to spatial mismatch nouns (*on the bowl*) and responses to conjunction match nouns (*and the bowl*) in medial central and posterior sites (Cz and Pz). Compare red (spatial mismatch) and gray (conjunction match) waveforms to blue (spatial match) waveform in Figure 4.9 for averaged voltage across the scalp. See Figure D.19 in Appendix D for responses in this time window for all 11 regions.

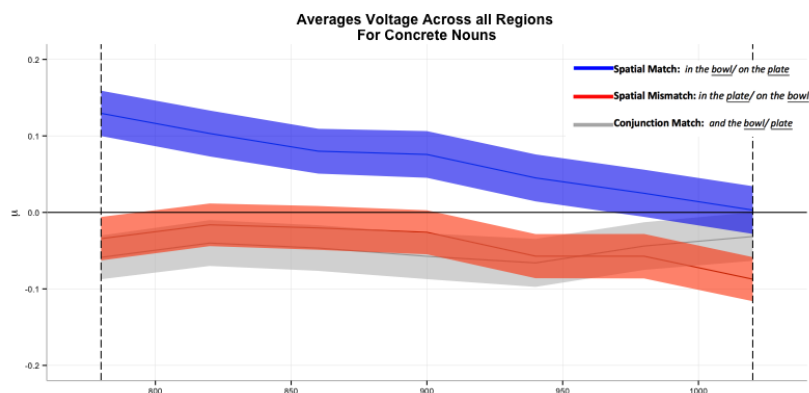


Figure 4.9: Responses to different reference noun types averaged across eleven spatial regions chosen from rotated components for fourth time window of interest post-noun onset. Gray is conjunction match, blue is spatial match, red is spatial mismatch (see legend at bottom right). Dotted lines represent beginning and end of fourth epoch of interest (780 to 1020ms post-noun onset).

The interaction between phrase type (spatial, headed by a preposition vs. non-spatial, headed by a conjunction) and hemisphere was also significant in this time window,  $F_{(2,54)} = 3.37$ ,  $p < 0.05$ ,  $\epsilon > 0.85$ , reflecting a pattern whereby responses to nouns in spatial phrases were more positive than responses to nouns in non-spatial phrases in medial regions (Fz, Cz, and Pz) and more negative in lateral occipital regions (O1 and O2). Compare purple waveforms (conjunction/non-spatial

phrases) and turquoise waveforms (preposition/spatial phrases) in Figure 4.10 and Figure 4.11.

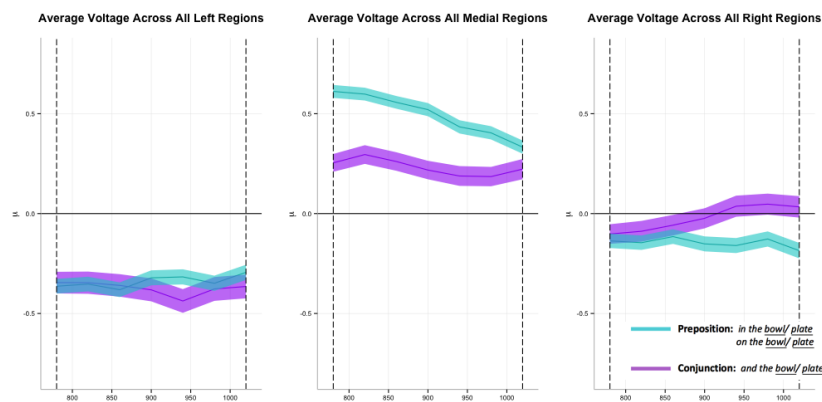


Figure 4.10: Responses to nouns averaged across hemisphere (left regions, medial regions and right regions) for fourth time window of interest post-noun onset for two different phrase types: Conjunction and preposition (averaged across spatial match and spatial mismatch). Turquoise lines represent averages across preposition phrases and purple is conjunction phrase (see legend at bottom right). Averaged across all four picture conditions for all phrases. Dotted lines represent beginning and end of fourth epoch of interest (780 to 1020ms post-noun onset).

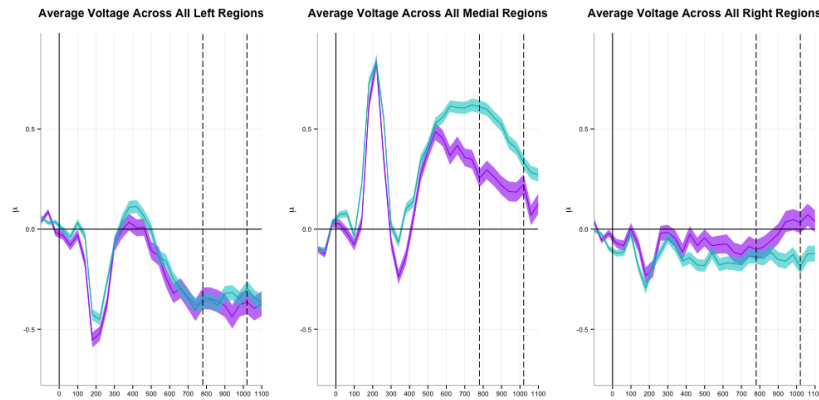


Figure 4.11: Responses to nouns averaged across hemisphere (left regions, medial regions and right regions) for fourth time window of interest post-noun onset for two different phrase types: Conjunction and preposition (averaged across spatial match and spatial mismatch). Turquoise lines represent averages across preposition phrases and purple is conjunction phrase (see legend at bottom right). Averaged across all four picture conditions for all phrases. Dotted lines represent beginning and end of fourth epoch of interest (780 to 1020ms post-noun onset).

Figure D.19 in Appendix D for responses in this time window for all 11 regions.

When only spatial nouns (after prepositions) were included in the comparisons, the interaction between the space of the reference noun (whether the space of the reference noun matched the preceding preposition or not) and anteriority was found to be significant,  $F_{(2,54)} = 3.62$ ,  $p < 0.05$ ,  $\epsilon > 0.75$ . In this time window, responses to spatial match nouns were more positive in central (C3, Cz, C4) and posterior regions (Pz, O1 and O2) than responses to spatial mismatch nouns, with an inverse effect (spatially matched nouns yielding relatively *negative* responses) in frontal regions (Fz and F8). Figure 4.12 displays averaged responses across

frontal and posterior regions to spatial match and mismatch nouns for this time window.

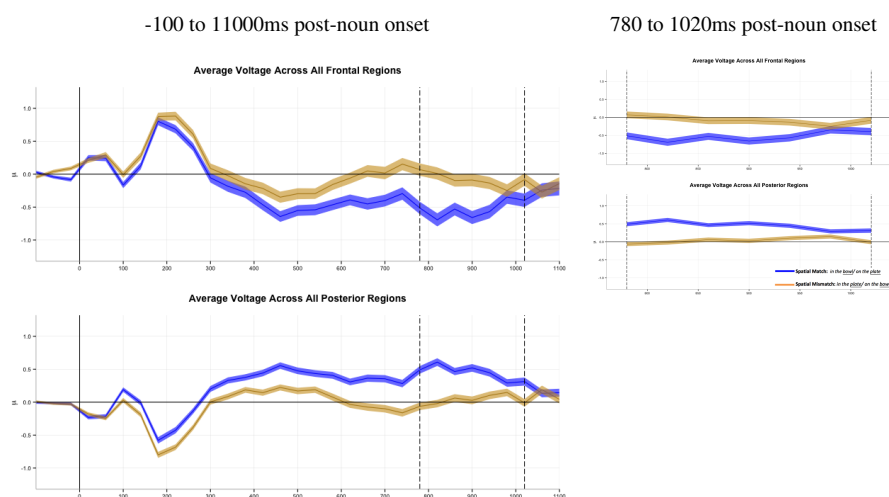


Figure 4.12: Responses to Space Match (blue) and Space Mismatch (orange) nouns for fourth time window of interest averaged across frontal (F7, Fz, and F8) and posterior (P7, Pz, and P8) regions. Start and end of fourth time window of interest (780 to 1020ms) is indicated by dotted lines.

Responses in Figure D.21 in Appendix D shows responses to spatial match and mismatch nouns for this time window at all 11 regions of interest.

#### 4.2.1.5 1060-1220 milliseconds

From 1060 milliseconds post-noun-onset to 1220ms post-noun onset (the end of the time period within which the noun was displayed on the screen), the interaction between phrase type (spatial, headed by a preposition vs. non-spatial, headed by a conjunction) and hemisphere was significant,  $F_{(2,54)} = 3.59$ ,  $p < 0.05$ ,  $\epsilon > 0.90$ .

Responses to nouns in spatial phrases were more positive than responses to nouns in non-spatial phrases in medial regions (Fz, Cz, and Pz) and more negative in right regions (P8 and O2). See Figure 4.13 for responses to nouns in preposition and conjunction phrases, averaged across left, right and medial regions for just this time window, and see Figure 4.14 for responses to nouns in preposition and conjunction phrases, averaged across left, right and medial regions for the entire epoch, with this time window highlighted.

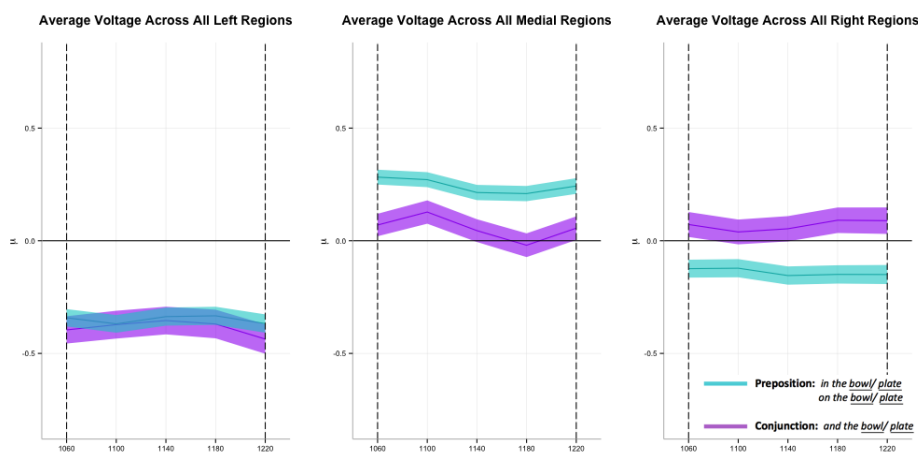


Figure 4.13: Responses to nouns averaged across hemisphere (left regions, medial regions and right regions) for fourth time window of interest post-noun onset for two different phrase types: Conjunction and preposition (averaged across spatial match and spatial mismatch). Turquoise lines represent averages across preposition phrases and purple is conjunction phrase (see legend at bottom right). Averaged across all four picture conditions for all phrases. Dotted lines represent beginning and end of last epoch of interest (1060 to 1220ms post-noun onset).



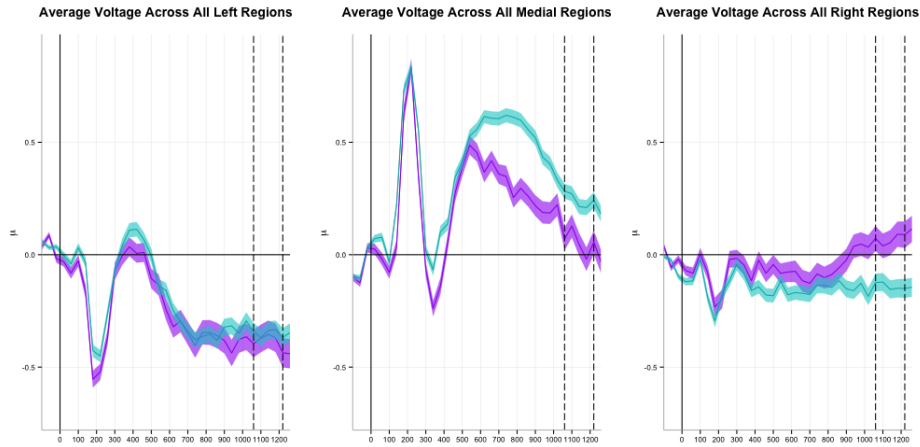


Figure 4.14: Responses to nouns averaged across hemisphere (left regions, medial regions and right regions) for fourth time window of interest post-noun onset for two different phrase types: Conjunction and preposition (averaged across spatial match and spatial mismatch). Turquoise lines represent averages across preposition phrases and purple is conjunction phrase (see legend at bottom right). Averaged across all four picture conditions for all phrases. Dotted lines represent beginning and end of last epoch of interest (1060 to 1220ms post-noun onset).

See Figure D.4 in Appendix D to compare responses to spatial phrases (turquoise) to conjunction phrases (purple) for this time window for all 11 regions of interest.

During this last time window, the interaction between reference noun type (spatial match, spatial mismatch, conjunction match) and the object in the picture (no picture, matching object, mismatching object) was marginally significant  $F_{(4,108)} = 2.41, p < 0.06, \epsilon = 1$ . For spatial match phrases, responses to nouns after pictures of random objects were positive, as compared to responses to these nouns after pictures of matching objects. For conjunction match phrases, responses to nouns

after pictures of random objects were most negative, as compared to responses to these nouns after pictures of matching objects. No pattern was evident for spatial mismatch phrases. Compare responses in Figure 4.15.

Responses at Pz for Conjunction Match (e.g., "and the plate"), Space Match ("on the plate"), and Space Mismatch ("in the plate")

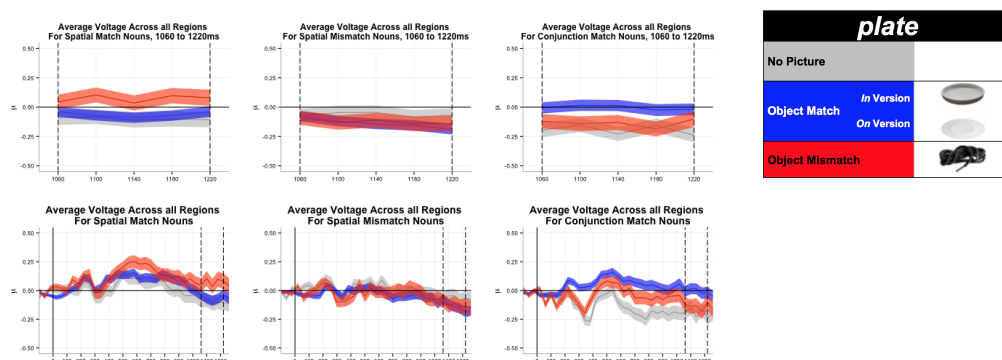
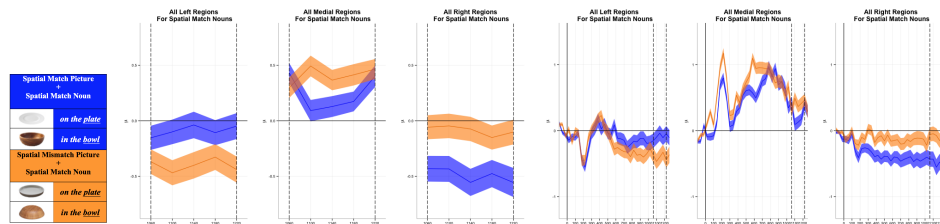


Figure 4.15: Responses averaged across all regions to spatial match, spatial mismatch and conjunction match nouns in after seeing no picture (gray), a picture of a matching object (blue), and a picture of a random object (red). See legend at right.

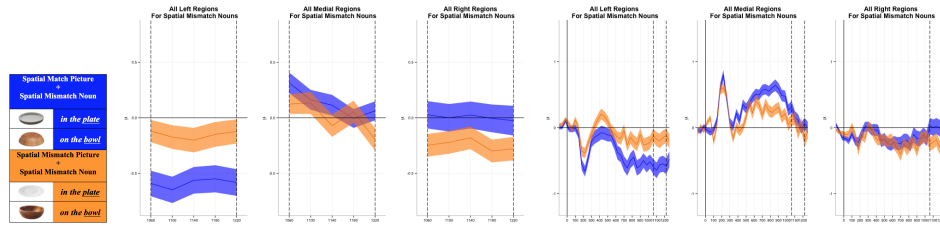
For comparisons that included only the spatial nouns (after prepositions), the three-way interaction between the space of the reference noun (match or mismatch), the spatial configuration of the object depicted in the picture (whether it matched the preposition preceding the noun or not) and hemisphere was significant,  $F_{(2,54)} = 4.33$ ,  $p < 0.05$ ,  $\epsilon > 0.90$ . During this time window, the spatial match nouns (e.g., *bowl* and *plate* in *in the bowl/on the plate*, respectively) yielded more negative ERPs in right regions (F8, P8, and O2) after spatially matching pictures were displayed (e.g., an open-side-up bowl or a flat plate, respectively) than when spatially mismatched pictures were displayed (e.g., an open-side-down bowl or a

concave plate, respectively). The opposite effect was apparent in left frontal (F7) and left central (C3) regions, where responses to spatially matched nouns were more positive after spatially matching pictures than spatially mismatching pictures. For spatially *mismatching* nouns (e.g., *bowl* and *plate* in *on the bowl/in the plate*, respectively), there was a left-lateralized negativity after spatially matching pictures (e.g., an open-side-down bowl and a concave plate, respectively) in left frontal and posterior regions (F7, P7 and O1) with an opposite effect in medial and right frontal and central (Fz, F8, C4, and Cz) regions. To show the relationship between laterality and condition for this time window, Figure 4.16, Sub-Figures 4.16b and 4.16e show responses to spatial match nouns and mismatch nouns averaged across regions used as left, medial and right hemisphere after pictures of spatially matching and spatially mismatching objects between 1060 and 1220ms post-noun onset for spatial match nouns (top row) and spatial mismatch nouns (bottom row), respectively. In order to see the way that responses to nouns change across time depending on the way objects are displayed in the preceding picture, Sub-Figures 4.16c and 4.16f show these same waveforms for the entire epoch that the nouns are on the screen.



Responses averaged across sites in three hemisphere regions (Left, Medial, Right) for spatially matched nouns ("in the bowl"/"on the plate") after spatially matching pictures (e.g., an open-side-up bowl or a flat plate, respectively) and spatially mismatching pictures (e.g., an open-side-down bowl or a concave plate, respectively) during last epoch of interest.

Responses averaged across sites in three hemisphere regions (Left, Medial, Right) for spatially matched nouns ("in the bowl"/"on the plate") after spatially matching pictures (e.g., an open-side-up bowl or a flat plate, respectively) are shown (waveform in blue) and spatially mismatching pictures (e.g., an open-side-down bowl or a concave plate, respectively) during whole epoch. Dotted lines represent beginning and end of epoch of interest (1020 to 1260ms post-noun onset.)



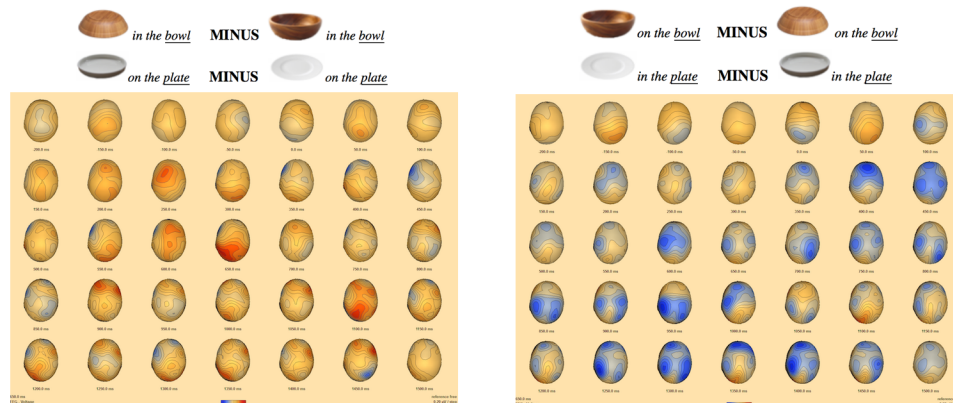
Responses in averaged across sites in three hemisphere regions (Left, Medial, Right) for spatially mismatched nouns ("in the bowl"/"on the plate") after spatially matching pictures (e.g., an open-side-down bowl or a concave plate, respectively) are shown and after a spatially mismatching pictures (e.g., an open-side-up bowl or a flat plate, respectively) during last epoch of interest.

Responses in averaged across sites in three hemisphere regions (Left, Medial, Right) for spatially mismatched nouns ("in the bowl"/"on the plate") after spatially matching pictures (e.g., an open-side-down bowl or a concave plate, respectively) are shown and after a spatially mismatching pictures (e.g., an open-side-up bowl or a flat plate, respectively) during whole epoch. Dotted lines represent beginning and end of epoch of interest (1020 to 1260ms post-noun onset).

Figure 4.16: Responses to nouns after spatially matching pictures and spatially mismatching pictures for spatial match (top row) and mismatch (bottom row) nouns. See legends at left for picture examples for each phrase type.

In Figure 4.17, Sub-Figures 4.17a and 4.17b show topographic plots of differences when responses to nouns after spatially matching pictures are subtracted from responses to nouns after spatially mismatching pictures for spatial match

and mismatch nouns, from 0 to 1500ms post-noun onset.



Difference between voltage when responses to spatially matched nouns ("in the bowl"/"on the plate") after spatially matching pictures (e.g., an open-side-up bowl or a flat plate, respectively) are subtracted from responses to spatially matched nouns after spatially mismatching pictures (e.g., an open-side-down bowl or a concave plate, respectively)

Difference between voltage when responses to spatially mismatched nouns ("on the bowl"/"in the plate") after spatially matching pictures (e.g., an open-side-up bowl or a flat plate, respectively) are subtracted from responses to spatially matched nouns after spatially mismatching pictures (e.g., an open-side-down bowl or a concave plate, respectively)

Figure 4.17: Topographic plots across the entire recording epoch of difference activity when responses to nouns after spatially matching pictures are subtracted from responses to nouns after spatially mismatching pictures. Left plot is differences for spatial match nouns and right is plot of differences for spatial mismatch nouns. See legends at top of each plot for example pictures/phrases used for subtractions.

## 4.2.2 Abstract reference nouns

For the abstract reference nouns, a temporal PCA yielded five time regions of interest: 152-332ms, 352-500ms, 676-876ms, 900-1100ms and 1100-1248ms. These time windows were used to perform an exploratory spatial PCA (with a Varimax rotation) in order to select electrode regions within which the activity recorded at individual electrodes in the region co-varied. The rotated components from these

time windows identified nine sets of six electrodes that co-varied across all five time windows. These regions, displayed in Figure 4.18, were the following: left frontal including F7, central frontal including Fz, right frontal including F8, left central including C3, central including Cz, right central near C4, left posterior including P7, central posterior including Pz, and right posterior inferior to P8.

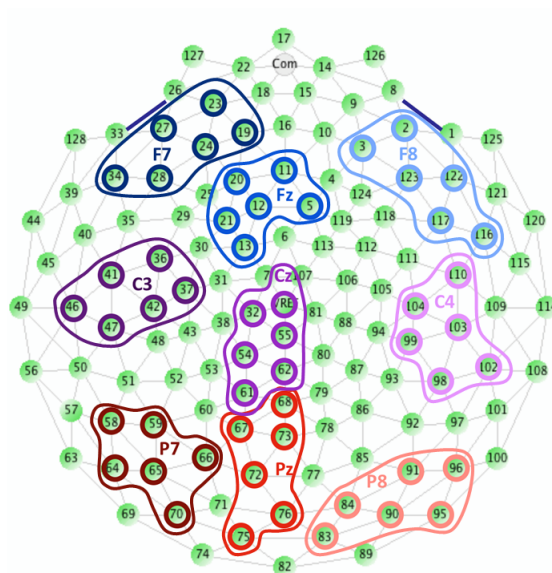


Figure 4.18: Nine regions selected from rotated components from five time windows for abstract reference nouns.

These 9 regions were then categorized for laterality/hemisphere and anteriority. Frontal regions were F7, Fz, and F8. Central regions were C3, Cz and C4. Posterior regions were P7, Pz, and P8. Left regions were F7, C3, and P7. Medial regions were Fz, Cz and Pz. Right regions were F8, C4, and P8.

Data from -200 milliseconds before the onset of the visual presentation nouns to 1250 ms post-noun onset were down-sampled in IGOR Pro, so that each data-

point represented activity from 40-millisecond intervals (to a sampling rate of 25Hz). The time-averaged data were imported into R-Studio and were further averaged into five time windows corresponding to those identified by the temporal PCA: 160-320ms, 360-500ms, 680-880ms, 880-1080ms, and 1120-1240ms. In R-Studio, averaged voltage across these time intervals of interest was subjected to repeated-measure ANOVAs by participant with the dependent factors: Reference Object Type (abstract match, abstract mismatch), Anteriority (frontal, central, posterior), and Hemisphere (left, right, medial). A secondary set of repeated-measure ANOVAs were conducted for just the items when phrases followed pictures of spatially matching/mismatching objects, with the factors: Space in Picture (Whether the spatial configuration of the object matched the preposition in the phrase), Anteriority (frontal, central, posterior) and Hemisphere (left, right, medial). Mauchly's sphericity tests were conducted on all comparisons of factors with two or more levels (Reference noun type, Hemisphere, Anteriority) and interactions between factors (when there was greater than one degree of freedom in the numerator). A Huynh-Feldt correction was applied in order to correct for possible violations to assumptions of sphericity (Huynh and Feldt 1976). The critical  $p$  value was 0.05. The critical  $p$  value was 0.05. In Table 4.4, all significant ( $p \leq 0.05$ ) and marginally significant ( $p < 0.1$ ) effects are displayed. In the text, only effects with  $p \leq 0.07$  are discussed.

TIME	EFFECT	<i>F</i>	$\epsilon$	<i>p</i>		
160-320ms	Picture * Anteriority * Hemisphere	<i>F</i> (12, 324)	2.44	0.72	0.01	*
360-500ms	Space in Picture	<i>F</i> (1, 27)	6.56	N/A	0.02	*
	Space in Picture * Anteriority	<i>F</i> (2, 54)	3.42	0.91	0.05	*
1120-1240ms	Reference Noun * Hemisphere	<i>F</i> (2, 54)	2.61	0.95	0.09	.

Table 4.4: Results of repeated-measures ANOVAs by participant at onset of abstract nouns for the three of five time windows of interest in which there were significant (*p* value under 0.05) or marginally significant (*p* value < 0.1) effects, after the Huynh-Feldt correction (when applicable, i.e., when factors had more than two levels).

For the sake of parsimony, only significant effects relevant to the research questions and predictions for this study are reported in the following sections. For all time windows of interest, either the main effect of anteriority or hemisphere and/or the interaction of these two factors had a significant impact on voltage. However, because these effects do not inform the research questions and hypotheses (about the effects of picture and/or phrase type on ERPs), they are not reported.

#### 4.2.2.1 160-320 milliseconds

There was a significant interaction between the type of picture shown before the phrases (no picture, spatially matching object, spatially mismatching object, and random object), anteriority, and hemisphere,  $F_{(12,324)} = 2.44$ ,  $p < 0.05$ ,  $\epsilon > 0.72$ .



Responses to abstract nouns after seeing pictures of random objects were relatively positive in left frontal sites (F7) and in the medial central region (Cz) as compared to responses after seeing other pictures. Conversely, responses to abstract nouns after seeing pictures of random objects are most negative in left central regions (C3), as compared to responses to abstract nouns after the presentation of spatially matching/mismatching pictures or no pictures. See red waveform in Figure 4.19, which reflect responses to abstract nouns after the presentation of photographs of random objects. Responses to abstract nouns after seeing pictures of spatially matching (blue waveform in Figure 4.19) pictures are most negative (as compared to no picture, picture of spatially matching object and picture of random object) in left and medial frontal sites (F7 and Fz) and most positive in left and medial posterior sites (P7 and Pz). Responses to abstract nouns after seeing a picture of a spatially mismatching object (orange waveform in Figure 4.19) are most negative during this window in left and medial posterior regions (Pz and P7), and responses to abstract nouns after seeing no picture (gray waveform in Figure 4.19) are most negative (as compared to three other picture types) in right posterior regions (P8) and most positive in medial frontal (Fz) and left central (C3) regions.

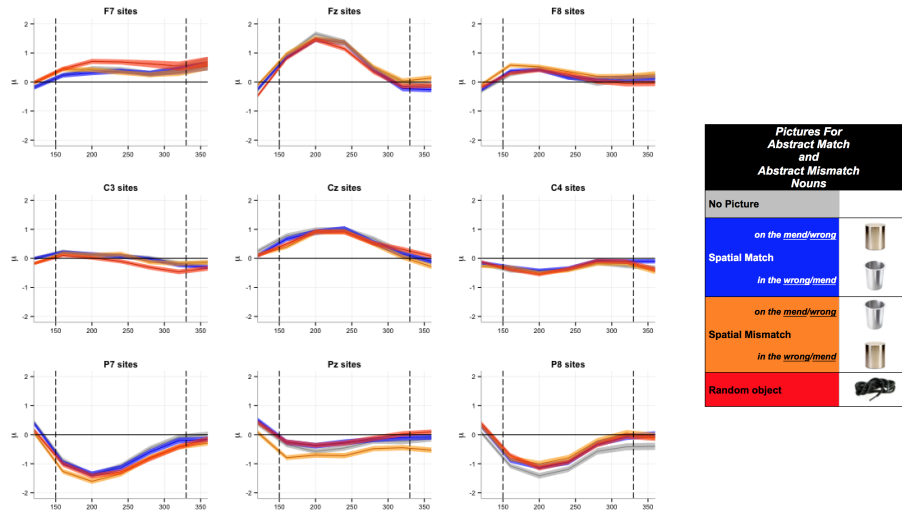


Figure 4.19: Responses to abstract phrases after different picture types in first epoch of interest. Gray waveforms are after no picture, blue after a picture of a spatially matching object, orange after a picture of a spatially mismatching object, and red after a picture of a random object. Dotted lines represent beginning and end of epoch of interest (160 to 320ms post-noun onset).

#### 4.2.2.2 360-500 milliseconds

Between 360 and 500 milliseconds after the onset of the abstract nouns, when just the experimental items (those that presented abstract phrases after spatially matching and mismatching photographs of objects) were included in comparisons, the main effect of the spatial properties of the picture (between spatially matching and mismatching pictures) had a significant impact on voltage,  $F_{(1,27)} = 6.56, p < 0.05$ , as did the interaction between the spatial properties of the photograph and anteriority,  $F_{(2,54)} = 3.42, p < 0.05$ . These results reflect a pattern where responses to abstract nouns after the presentation of spatially mismatching photographs were

more negative in left and medial posterior regions (P7 and Pz) and more positive in anterior regions (F7, Fz, and F8) as compared to responses to the same nouns after the presentation of spatially matching objects between 300 and 600ms post-noun onset. See Figure 4.20, which shows difference waves at frontal and posterior regions. The difference waves represent a subtraction of responses to abstract nouns after spatially matching pictures from responses to the same nouns after spatially mismatching pictures.

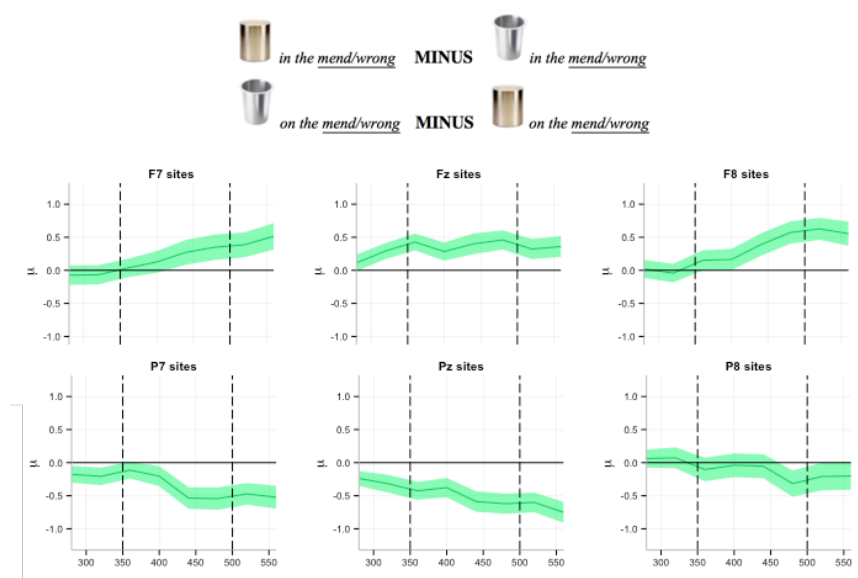


Figure 4.20: Difference between voltage when responses to abstract nouns (e.g., *in the wrong/mend*, *on the mend/wrong*) after spatially matching pictures (i.e., a container object for *in* phrases and a surface object for *on* phrases) are subtracted from responses to abstract nouns after spatially mismatching pictures (i.e., a container object for *on* phrases and a surface object for *in* phrases) for second epoch of interest, indicated by dotted lines (at 360ms and 500ms).

#### 4.2.2.3 680-880 milliseconds

For this time window, neither phrase type nor picture type had a significant impact on voltage, nor did the interaction between these two factors, nor did the interaction between either or both of these factors and anteriority or hemisphere. There were no effects approaching significance ( $p < 0.1$ ) for this time window either.

#### 4.2.2.4 880-1080 milliseconds

For this time window, neither phrase type nor picture type had a significant impact on voltage ( $p < 0.05$ ), nor did the interaction between these two factors, nor did the interaction between either or both of these factors and anteriority or hemisphere. There were no effects approaching significance ( $p < 0.1$ ) for this time window either.

#### 4.2.2.5 1120-1240 milliseconds

For this time window, neither phrase type nor picture type had a significant impact on voltage ( $p < 0.05$ ), nor did the interaction between these two factors, nor did the interaction between either or both of these factors and anteriority or hemisphere.

The interaction between reference noun type (Abstract match [*in the red/on the verge*] versus Abstract mismatch[*on the red/in the verge*]) and Hemisphere was

marginally significant,  $F_{(2,54)} = 2.61$ ,  $p < 0.09$ ,  $\epsilon > 0.95$ , reflecting a pattern where responses to abstract mismatch phrases were more positive than responses to abstract match phrases in medial regions (Fz, Cz, and Pz) and more negative than responses to abstract match phrases in left and right frontal and posterior regions (F7, F8, P7 and P8). See Figure D.23 in Appendix D for responses to abstract match and mismatch nouns at all sites across the entire noun epoch.

### 4.3 ERP results for concrete prepositions and conjunctions

For the prepositions and conjunction epochs (500 milliseconds long), the temporal PCA yielded four time windows of interest post-preposition or -conjunction onset: 100-160ms, 164-228ms, 232-324ms, and 364-480ms. In order to explore the possibility of an effect of spatial language on slow-wave activity as reported by Noordzij et al. (2006), an additional time interval, from 548-1000ms post-stimulus onset<sup>4</sup>, was also included. During this time window, the definite determiner *the* was presented on the screen.

These time windows were used to perform an exploratory spatial PCA in order to

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<sup>4</sup>Actually, slow-wave activity in Noordzij et al. (2006) was reported until 1050ms post phrase onset. However, in their study, phrases were presented at once, while the current study presents words one-by-one. In the current study, the reference noun - which determines whether the phrase is matching or mismatching - begins 1000ms after the onset of the preposition. Therefore, activity beyond 1000ms post-preposition-onset is excluded from the analysis of preposition phrase epochs, under the assumption that this activity might reflect predictive and interpretative processes involving the reference noun, and not general spatial-language processing mechanisms.

identify electrode groupings to use for the analyses. The rotated components identified ten sets of electrodes for which the activity recorded at individual electrodes co-varied across the five time windows; These regions, displayed in Figure 4.21, included the following: left frontal including F7, medial frontal including Fz, right frontal including F8, left central including C3, central including Cz, right central including C4, left posterior including P7, medial posterior including Pz, right posterior including P8, and an occipital region below O1 and O2.

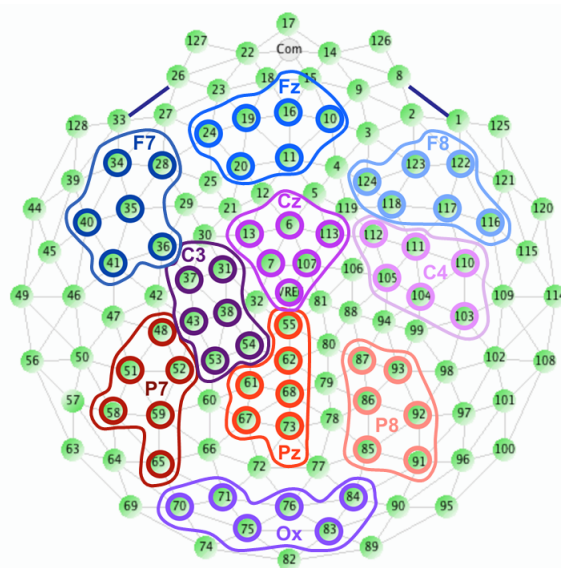


Figure 4.21: Ten regions selected from rotated components from five time windows.

Nine of these 10 regions were then categorized for laterality/hemisphere and anteriority for the analysis. The occipital region ("Ox") was excluded from the ANOVAs<sup>5</sup>, so that an equal number of sites/regions were included in the Hemisphere factor

<sup>5</sup>But still displayed in the Figures shown in this section, so that activity in this region is visible.

and Anteriority factor. Frontal regions were F7, Fz, and F8. Central regions were C3, Cz and C4. Posterior regions were P7, Pz, and P8. Left regions were F7, C3, and P7. Medial regions were Fz, Cz and Pz. Right regions were F8, C4, and P8.

Data from -300 ms before the onset of the prepositions to 2000 ms post-preposition onset were down-sampled and time averaged in IGOR Pro, so that each data-point represents activity from 40-millisecond intervals (approximating data at a sampling rate of 25Hz). The time-averaged data were imported into R-Studio and were further averaged into five time windows of interest, corresponding to the time windows post-preposition onset identified by the temporal PCA: 100-140ms, 180-220ms, 260-300ms, 380-460ms, 540-980ms. Averages for each time window of interest are subjected to repeated-measure ANOVAs by participant with the factors phrase type (Preposition or Conjunction), Object in Picture (No Picture, *In/On* Object, Random Object), Anteriority (Frontal, Central, Posterior), and Hemisphere (Left, Right, Medial). A Huynh-Feldt correction was applied in order to correct for possible violations to assumptions of sphericity (Huynh and Feldt 1976, Noordzij et al. 2006). The critical  $p$  value was 0.05. The critical  $p$  value was 0.05. In Table 4.5, all significant ( $p \leq 0.05$ ) and marginally significant ( $p < 0.1$ ) effects are displayed. In the text, only effects with  $p \leq 0.07$  are discussed.

A secondary set of repeated-measure ANOVAs was conducted for just the prepositional phrases with the factors Picture Type (No Picture, Spatially matching, Spatially mismatching, Random object) or Space in Picture (Whether the spatial

configuration of the object matched the preposition in the phrase), Anteriority (frontal, central, posterior) and Hemisphere (left, right, medial). The same regions as mentioned above were used for the left, right, and medial levels of the Hemisphere factor and for frontal, central, and posterior levels for the Anteriority factor. The critical  $p$  value was again 0.05.

TIME	EFFECT	F	$\epsilon$	p
100-140ms	Phrase * Hemisphere $F(2, 54)$	4.14	1.04	0.0213 *
	Phrase * Object in Picture $F(2, 54)$	3.89	1.071	0.0264 *
180-220ms	Phrase * Hemisphere $F(2, 54)$	3.48	1.07	0.0379 *
	Phrase * Object in Picture $F(2, 54)$	4.81	0.962	0.0130 *
	Picture $F(3, 81)$	4.24	0.868	0.0111 *
	Picture * Anteriority $F(6, 162)$	2.56	0.754	0.0358 *
260-300ms	Phrase * Hemisphere $F(2, 54)$	8.93	0.987	0.0005 ***
	Phrase * Object in Picture $F(2, 54)$	3.43	0.992	0.0401 *
	Picture $F(3, 81)$	2.53	0.722	0.0840 .
380-460ms	Object in Picture * Anteriority $F(4, 108)$	3.25	0.811	0.0226 *
	Object in Picture * Anteriority * Hemisphere $F(8, 216)$	2.1	0.781	0.0536 .
	Picture $F(3, 81)$	2.4	0.888	0.0820 .
	Picture * Anteriority $F(6, 162)$	3.54	0.967	0.0029 **
	Picture * Hemisphere $F(6, 162)$	1.99	0.889	0.0795 .
560-980ms	Phrase * Hemisphere $F(2, 54)$	3.79	0.953	0.0310 *
	Object in Picture * Anteriority $F(4, 108)$	3.54	0.927	0.0114 *
	Object in Picture * Anteriority * Hemisphere $F(8, 216)$	3.15	0.715	0.0069 **
	Picture * Anteriority $F(6, 162)$	2.96	0.791	0.0162 *
	Space in Picture $F(1, 27)$	3.67	N/A	0.0662 .

Table 4.5: Significant ( $p$  value under 0.05) or nearly significant ( $p$  value near 0.1) effects of repeated-measures ANOVAs by participant at the onset of prepositions within the five time windows of interest, after the Huynh-Feldt correction when applicable (i.e., when factors have more than two levels).



### 4.3.1 100-140 milliseconds

In the earliest time window, from 100 to 140 milliseconds post-onset of the preposition or conjunction, the interaction between phrase type (preposition or conjunction) and hemisphere (left, right, medial) makes a significant impact on voltage,  $F_{(2,54)} = 4.14, p < 0.05, \epsilon = 1$ . During this time, responses to conjunction phrases were slightly more negative than they were to prepositional phrases in right and medial regions, and slightly more positive in left regions. Compare turquoise (preposition) and purple (conjunction) waveforms in Figure 4.22 to see averages across left and right regions for this time window. See Figure D.24 in Appendix D to see responses at all regions across the entire epoch.

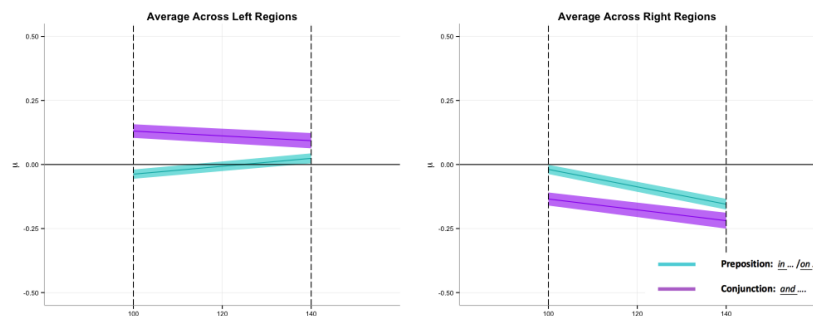


Figure 4.22: Responses to prepositions and conjunctions averaged across left (F7, C3, and P7) and right (F8, C4, and P8) regions for the first time window of interest (100 to 140 milliseconds post-preposition or -conjunction onset). Turquoise is Preposition Phrase and purple is Conjunction Phrase.

There was also a significant interaction between phrase type (conjunction or preposition) and what *type* of object was depicted in the photograph displayed before the phrase (no object, an object whose spatial characteristics match either *in* or

*on* [i.e., a bowl or a plate, respectively] or an object whose spatial characteristics do not match either *in* or *on* [i.e., a banana or a pen]),  $F_{(2,54)} = 3.89$ ,  $p < 0.05$ ,  $\epsilon = 1$ . During this time window, responses to prepositions after seeing pictures of objects with spatial characteristics that did not match either *in* or *on* were more negative (across all regions) than responses to prepositions after seeing an object with spatial characteristics that matched either *in* or *on* and after seeing no picture at all. This difference did not occur in the responses to conjunctions. Compare waveforms in Figure 4.23, which shows responses to prepositions and to conjunctions across the entire scalp in this time window for the three different picture types (no picture, *in/on* object picture, and a picture of a random object whose spatial/functional properties do not match either *in* or *on*). See SubFigure D.27a and Subfigure D.27b in Figure D.27 in Appendix D for responses at all regions to prepositions and conjunctions after the different picture types across the entire epoch.

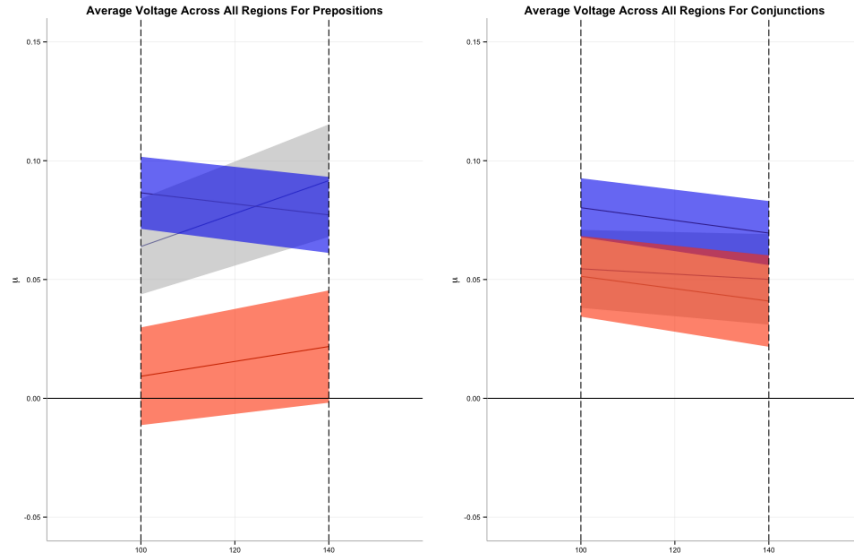


Figure 4.23: Responses to prepositions averaged across all 9 regions included in the analysis for the first time window of interest (100 to 140 milliseconds post-preposition or -conjunction onset) after different picture types. Gray is responses after no picture, blue is after picture of either *in* or *on* object, red is after picture of neither *in* nor *on* object.

### 4.3.2 180-220 milliseconds

In the next time window, there was again a significant interaction between phrase type (preposition or conjunction) and hemisphere, and again a significant interaction between phrase type and what object is presented before the phrase (no object, an *in/on* object, or an object whose spatial characteristics do not match *in* or *on*), respectively:  $F_{(2,54)} = 3.48, p < 0.05, \epsilon = 1$  and  $F_{(2,54)} = 4.81, p < 0.05, \epsilon > 0.95$ .

This time window included a large visual P2 in all frontal sites (F7, Fz, and F8)

and in Cz, with a corresponding N2 in lateral posterior sites, P7 and P8<sup>6</sup>. The same effect of phrase type observed in the previous time window rode atop the P2/N2 response, so that responses to prepositions remained more negative than conjunctions in left regions (F7, C3, and P7) and more positive than conjunctions in right regions (F8, C4, and P8). Figure 4.24 displays responses to preposition and conjunction phrases, averaged across regions in the left hemisphere (F7, C3, and P7) and the right hemisphere (F8, C4, and P8). See Figure D.24 in Appendix D to see responses at all regions across the entire epoch.

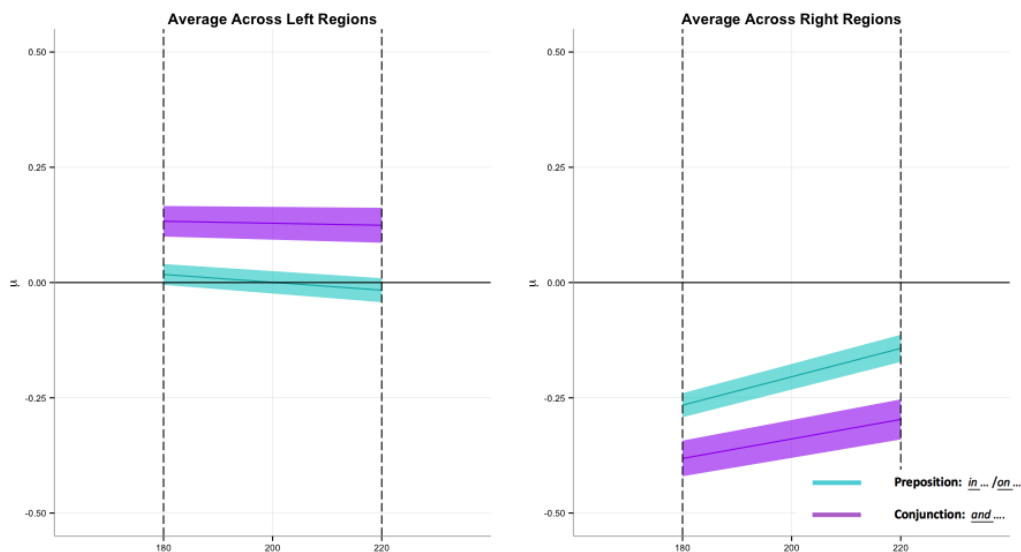


Figure 4.24: Responses to prepositions and conjunctions averaged left (F7, C3, and P7) and right (F8, C4, and P8) regions for the second time window of interest (180 to 220 milliseconds post-preposition or -conjunction onset). Turquoise is Preposition Phrase and purple is Conjunction Phrase.

Further, responses to prepositions were most negative at this visual P2 after see-

<sup>6</sup>And in occipital sites which are not included in these comparisons

ing a picture of an object with spatial/functional characteristics that did not match either *in* or *on* (e.g., a picture of a pen, apple or string), while for conjunctions, responses were most positive at this visual P2 after pictures of objects whose spatial/functional characteristics match neither *in* or *on*. Figure 4.23 shows responses to prepositions and to conjunctions across the entire scalp in this time window for the three different picture types (no picture, *in/on* object picture, and a picture of a random object whose spatial/functional properties do not match either *in* or *on*). See SubFigure D.27a and Subfigure D.27b in Figure D.27 in Appendix D for responses at all regions to prepositions and conjunctions after the different picture types across the entire epoch. For responses to conjunctions and prepositions for different picture types at all regions for the entire epoch, see Figure D.27 in Appendix D.

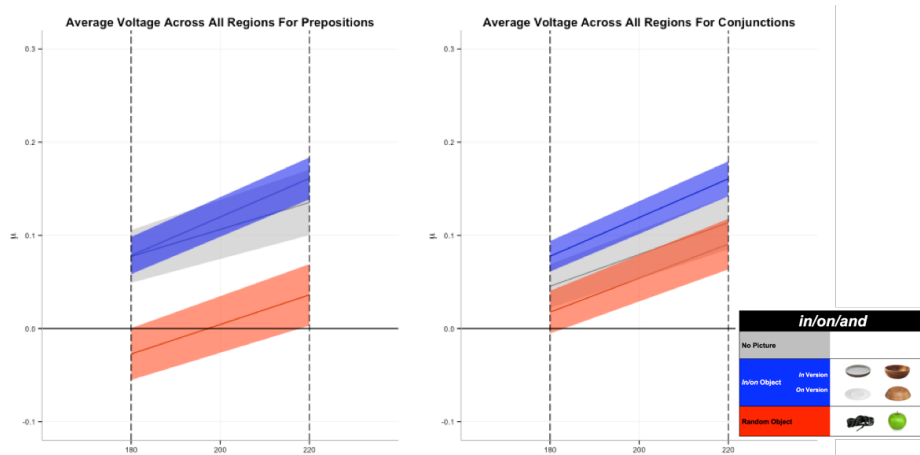


Figure 4.25: Responses to prepositions and conjunctions averaged across all 9 regions included in the analysis for the second time window of interest (180 to 220 milliseconds post-preposition or -conjunction onset). Blue waveform is response to prepositions/conjunctions after *in/on* objects, red waveform is response to prepositions/conjunctions after pictures of objects whose spatial/functional characteristics match neither *in* or *on*, gray is responses to prepositions/conjunctions after no picture.

When only the experimental phrases (prepositions) were included in comparisons, the main effect of specific picture type (No picture, Spatially matching, Spatially mismatching, and Random object) had a significant impact on voltage,  $F_{(3,81)} = 4.24$ ,  $p < 0.05$ ,  $\epsilon > 0.85$ , and so did the interaction between specific picture type and anteriority (Frontal, Central, Posterior),  $F_{(6,162)} = 2.56$ ,  $p < 0.05$ ,  $\epsilon > 0.70$ . Responses were significantly more negative after no picture was displayed than when a picture was displayed in posterior regions (P7, P8, and Pz), while being more positive in frontal regions (F7, F8, and Fz) and two of the three central regions (Cz and C4). Responses to prepositions when an *in* or *on* object was displayed beforehand yielded more positive responses at the onset of the preposition than

responses to phrases after no picture was presented or after a picture of an object whose spatial configuration did not match either *in* or *on* was presented. For responses at all regions for the entire epoch, see Figure D.28 in Appendix D.

### 4.3.3 260-300 milliseconds

For this time window, the interaction between phrase type (preposition or conjunction) and hemisphere was again significant,  $F_{(2,54)} = 8.93, p < 0.001, \epsilon > 0.95$ , reflecting the same effect described in earlier time windows, where responses to prepositions were more negative than conjunctions in left regions and more positive than conjunctions in right regions. Figure 4.26, below, shows responses averaged across left (F7, C3, and P7) regions and right (F8, C4, and P8) regions for prepositions and conjunctions during this time window. See Figure D.24 in Appendix D to see responses at all regions across the entire epoch.

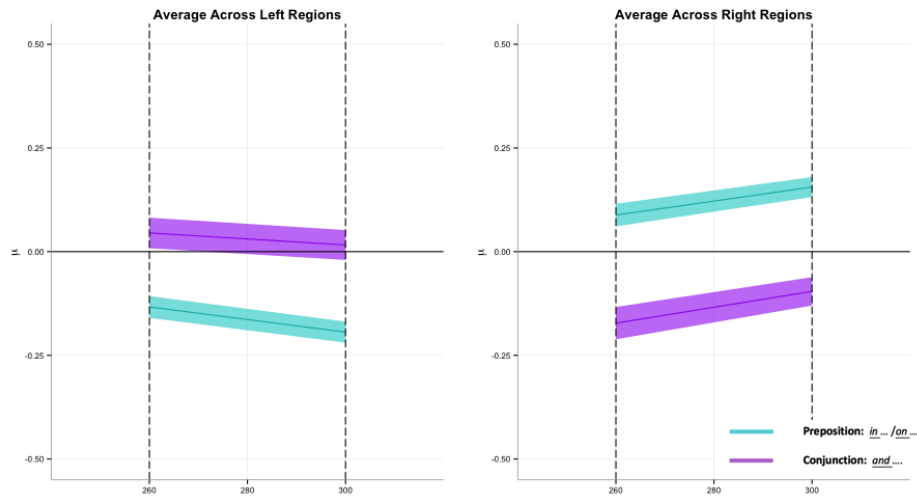


Figure 4.26: Responses to prepositions and conjunctions averaged across left (F7, C3, and P7) and right (F8, C4, and P8) regions for the third time window of interest (260 to 300 milliseconds post-preposition or -conjunction onset). Turquoise is Preposition Phrase and purple is Conjunction Phrase.

There was also a significant interaction between phrase type (preposition or conjunction) and object in picture (no object, *in/on* object, and random object),  $F_{(2,54)} = 3.43$ ,  $p < 0.05$ ,  $\epsilon > 0.95$ . Again, responses to prepositions were most negative after the presentation of pictures of objects with spatial/functional characteristics that did not match either *in* or *on*, while responses to conjunctions responses were most positive after the presentation of these pictures.

#### 4.3.4 380-460 milliseconds

In this time window, there was a significant interaction between the type of object presented in the photograph displayed before the picture (no object, *in/on* ob-



ject, or object whose spatial characteristics do not match *in* or *on*) and anteriority (frontal, central, and posterior), and a marginally significant three-way interaction between these effects and hemisphere,  $F_{(4,108)} = 3.25$   $p < 0.05$ ,  $\epsilon > 0.80$  and  $F_{(8,216)} = 2.1$   $p < 0.06$ ,  $\epsilon > 0.75$ , respectively. Responses to both prepositions and conjunctions after the presentation of no picture were more negative in posterior regions and more positive in frontal sites compared to responses to these words after the presentation of any picture (compare gray [no picture] waveforms to blue and red waveforms in Figure 4.27, below. Also see Figure D.27 in Appendix D to see separate waveforms for prepositions and conjunctions after these different picture types.

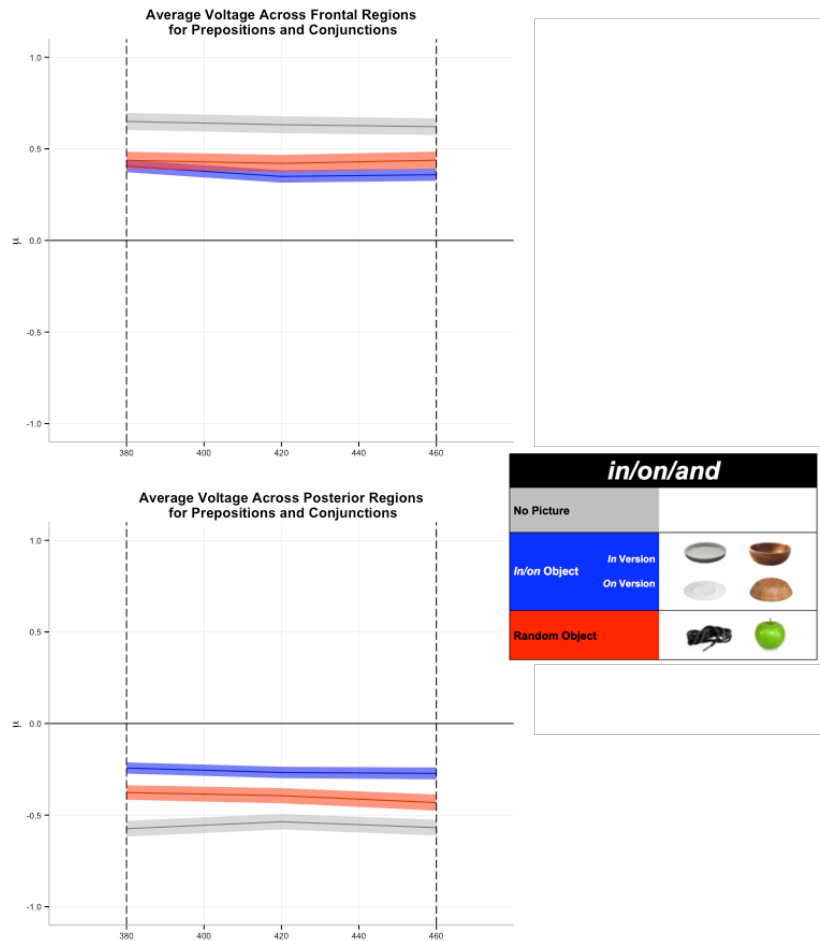


Figure 4.27: Responses to prepositions and conjunctions averaged across anterior (F7, Fz, and F8) and posterior (P7, Pz, P8) regions for the third time window of interest (380 to 460 milliseconds post-preposition or -conjunction onset). Blue waveform is response to prepositions/conjunctions after *in/on* objects, red waveform is response to prepositions/conjunctions after pictures of objects whose spatial/functional characteristics match neither *in* or *on*, gray is responses to prepositions/conjunctions after no picture

When just the prepositions were included in comparisons, there was also a significant interaction between specific picture type (no object, spatially matching ob-

ject, spatially mismatching object, and random object) and anteriority,  $F_{(6,162)}=3.54$   $p < 0.01$ ,  $\epsilon > 0.95$ . During this time window, responses to prepositions after seeing no object and after seeing a random object are more negative in posterior regions than after the presentation of spatially mismatching or matching objects.

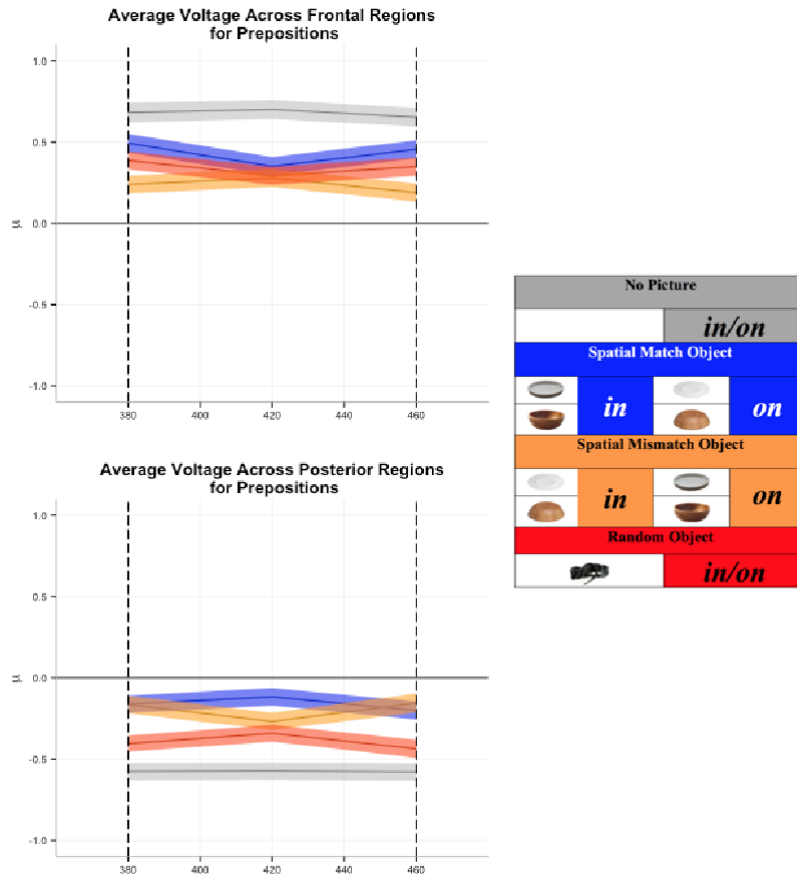


Figure 4.28: Responses to prepositions averaged across anterior (F7, Fz, and F8) and posterior (P7, Pz, P8) regions for the third time window of interest (380 to 460 milliseconds post-preposition onset). Blue waveform is response to prepositions after spatially matching objects, orange waveform is response to prepositions after spatially mismatching pictures, red waveform is response to prepositions after pictures of objects whose spatial/functional characteristics match neither *in* or *on*, gray is responses to prepositions/conjunctions after no picture

### 4.3.5 540-960 milliseconds

This last time window was explored because the slow-wave described by Noordzij et al. (2006), which they interpreted as indexing spatial-image-formation processes, was present from 550-1100 milliseconds after the onset of prepositional phrases<sup>7</sup>.

During this time window, the interaction between phrase type (preposition or conjunction) and hemisphere was again significant. Responses to spatial phrases after prepositions were more negative in most left and medial regions, but more positive in right regions,  $F_{(2,54)}=3.79$   $p < 0.05$ ,  $\epsilon > 0.90$ . See Figure 4.29, below.

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<sup>7</sup>This time window was not considered in the Principal Components Analysis, since it occurred after the time when the prepositions/conjunctions were displayed on the screen. In the study published by Noordzij et al. (2006), the entire prepositional/conjunction phrase was presented at once, whereas in the reported study, words were presented one-by-one. During the second half of this epoch (from 500ms-1000ms post-preposition or -conjunction onset), the preposition or conjunction had disappeared from the screen, and was replaced by the following definite determiner *the*.

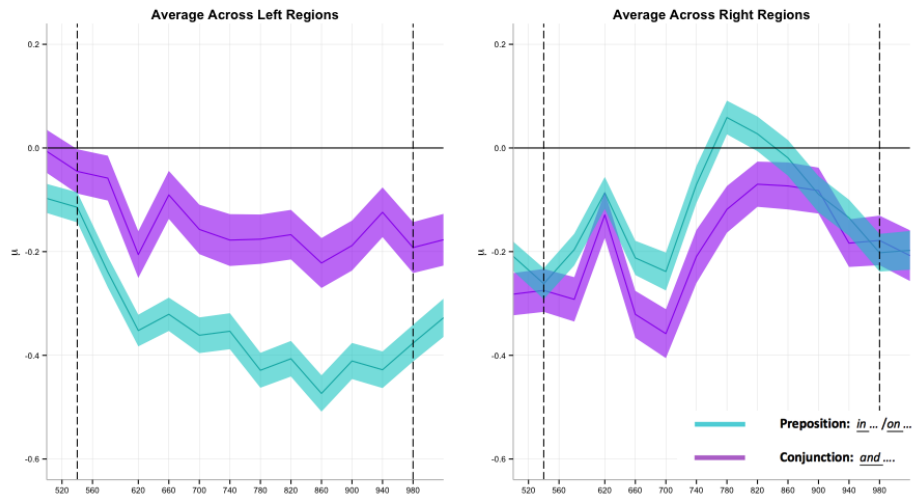


Figure 4.29: Responses to prepositions and conjunctions averaged across left (F7, C3, and P7) and right (F8, C4, and P8) regions for the last time window of interest (540 to 980 milliseconds post-preposition or -conjunction onset). Turquoise is Preposition Phrase and purple is Conjunction Phrase. Dotted lines mark start and end of epoch of interest.

There was a significant interaction between the type of object displayed in the photograph before the phrase (no object, *in/on* object, or object whose spatial characteristics do not match *in* or *on*) and anteriority (frontal, central, and posterior), along with a significant three-way interaction between the type of object shown in the photograph, anteriority and hemisphere (left, right, medial),  $F_{(4,108)} = 3.54 p < 0.05, \epsilon > 0.90, F_{(8,216)} = 3.15 p < 0.01, \epsilon > 0.75$ , where responses to both prepositions and conjunctions tended to be more negative after seeing no picture in left and medial posterior sites and more positive in frontal sites than responses to prepositions and conjunctions after seeing a picture of any object.

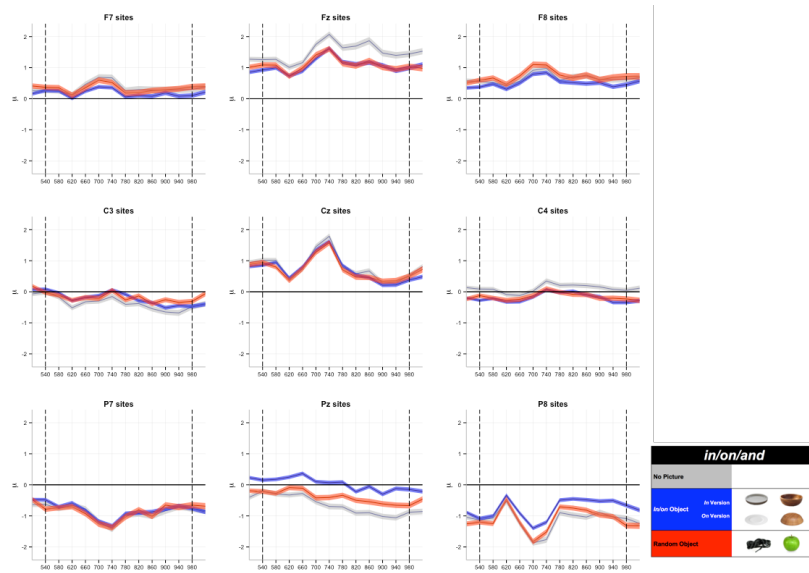


Figure 4.30: Responses to preposition and conjunction phrases for all 9 regions for the last time window of interest (540 to 980 milliseconds post-preposition or -conjunction onset). Blue waveform is response to preposition and conjunction phrases after *in/on* objects, red waveform is response to preposition and conjunction phrases after pictures of objects whose spatial/functional characteristics match neither *in* or *on*, gray is responses to prepositions/conjunctions after no picture.

When only the experimental phrases (prepositions) were included in the comparisons, the interaction between specific picture type (No picture, Spatially matching, Spatially mismatching, and Random object) and anteriority had a significant impact on voltage,  $F_{(6,162)} = 2.96$   $p < 0.05$ ,  $\epsilon > 0.75$ . In posterior regions, responses to phrases after seeing an object whose spatial properties or functional characteristics either matched *in* or *on* (regardless of which preposition was being displayed) were more positive than responses to prepositions when the preceding picture showed an object with spatial/functional properties that were not appro-

priate for either *in* or *on* or when there was no preceding picture at all. In frontal regions, responses to phrases after seeing no picture were relatively positive compared to responses to the phrases after the presentation of any picture. Responses to prepositional phrases were most negative in frontal regions when the picture shown before the phrase was spatially mismatching (i.e., the configuration of the object shown in the phrase was not appropriate for the preposition displayed. Figure 4.31 shows responses to prepositional phrases during this last time window for all four pictures types (during the time that the following determiner *the* is displayed on the screen), for frontal regions (averaged across F7, Fz, and F8) and for posterior regions (averaged across P7, Pz, and P8).



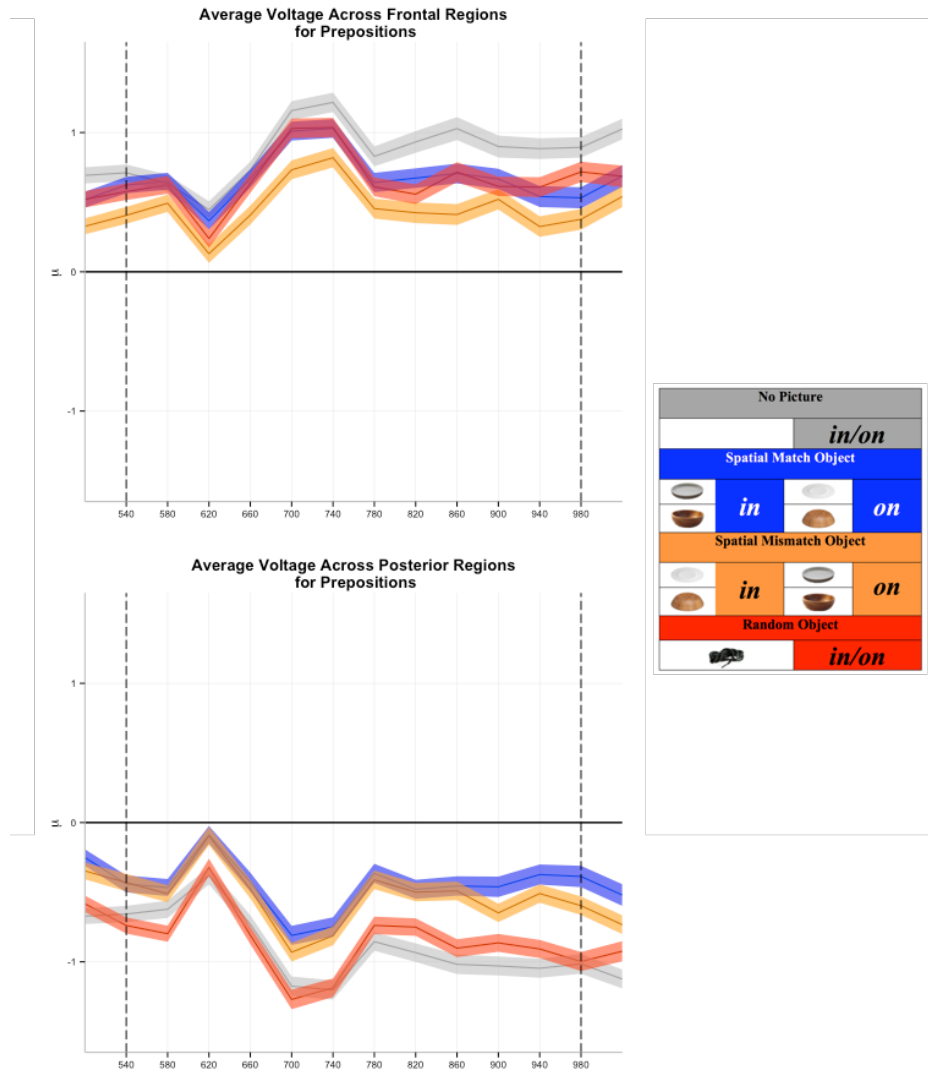


Figure 4.31: Responses to prepositional phrases averaged across anterior (F7, Fz, and F8) and posterior (P7, Pz, P8) regions included in the analysis for the last time window of interest (540 to 980 milliseconds post-preposition onset). Blue waveform is response to prepositional phrases after spatially matching objects, orange waveform is response to prepositional phrases after pictures of spatially mismatching objects, red waveform is response to prepositional phrases after pictures of objects whose spatial/functional characteristics match neither *in* or *on*, gray is responses to prepositional phrases after no picture.

## 4.4 Summary of results

### 4.4.1 Behavioral results

Overall, participants performed very well on the response task. Participants performed better on the questions following the space match and abstract match phrases as compared to their accuracy on questions following space mismatch and abstract mismatch phrases, respectively. They also performed better on questions following abstract phrases (compared to concrete phrases).

### 4.4.2 ERP responses

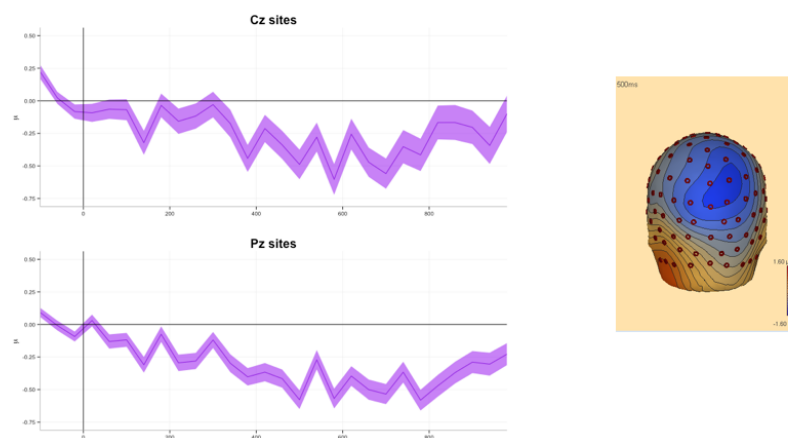
Both phrase type and picture type significantly affected ERPs to prepositions, conjunctions and nouns. These effects occurred during the predicted time windows for the N400 response (between 350 and 550ms for nouns and between 270 and 450ms for prepositions/conjunctions) and for occipital-parietal slow-wave activity (between 550 and 1000ms after the onset of the preposition in each phrase).

#### 4.4.2.1 Responses to nouns

##### 4.4.2.1.1 Concrete nouns

A medial centro-parietal N400 effect was elicited by the nouns in spatial mismatch phrases (e.g., *in the plate* and *on the bowl*) as compared to the nouns in

spatial match phrases (e.g., *on the plate* and *in the bowl*). The relative negativity to spatial mismatch nouns began at about 325ms post-noun-onset, peaked at around 550ms post-noun-onset, and continued until 1000ms post-noun-onset. Figure 4.32 highlights this response.



*in the plate/on the bowl* **MINUS** *on the plate/in the bowl*

Figure 4.32: Subtracted responses between spatial mismatch nouns and spatial match nouns (spatial mismatch- spatial match) at Cz and Pz. Right: Topomap of this subtraction at 500ms post-noun onset.

The effect of the type of picture shown before the phrase had a marginally significant impact on ( $p < 0.07$ ) responses 340-460 milliseconds post-noun onset. This result reflects relatively larger N400 responses to nouns after mismatching pictures (pictures of random objects) and after no pictures at all, see Figure 4.33.

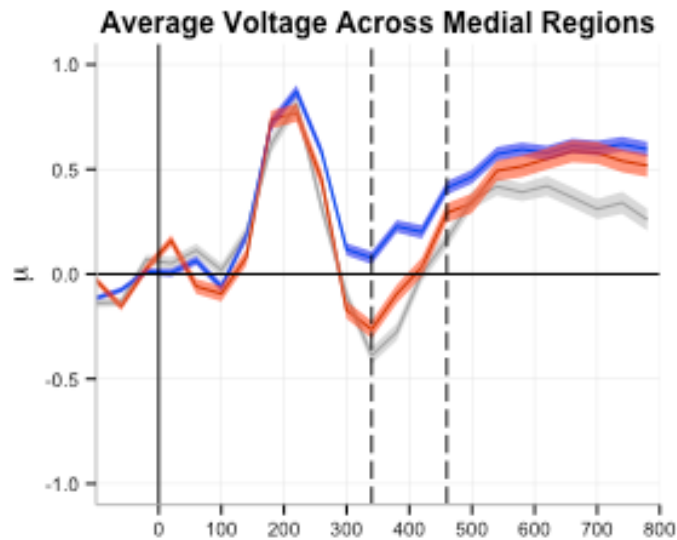


Figure 4.33: Responses to concrete nouns in medial regions after picture of no object (gray), picture of matching object (blue), or picture of random object (red).

This effect was largest in Cz and Pz regions, which were the same regions where N400 effect to phrase type (with relatively larger N400 responses to nouns in spatial mismatch and conjunction phrases than to spatial match nouns) was observable, and showed an interaction with phrase type, so that N400 modulations caused by the object in the picture were greatest for conjunction match and spatial mismatch phrases, compared to spatial match phrases.

While a classic, centro-parietal N400 was obvious after the onset of nouns when they were presented after pictures of random objects, this N400 was not observable for the nouns after the presentation of spatially mismatching objects. However, in both cases (after a picture of a random object and after a picture of a

spatially mismatching object), a frontal negativity, peaking in left/medial regions, was elicited. When nouns in spatial phrases were presented after spatially mismatching pictures, this relative negativity peaks right at 400ms post-noun onset and ends at about 600ms post-noun onset.

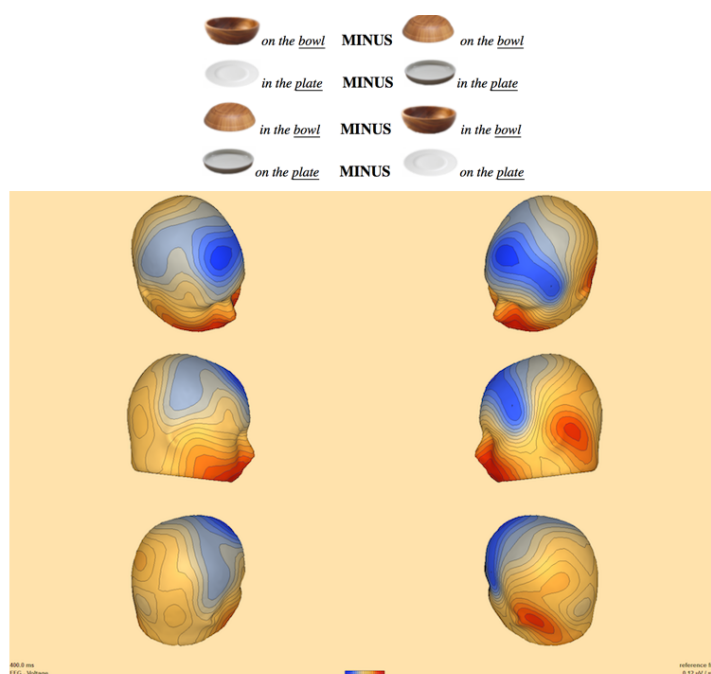


Figure 4.34: The result at 400ms post-nouns onset when responses to spatial nouns shown after spatial match pictures are subtracted from responses to the same nouns presented after spatial mismatch pictures.

The frontal negativity was larger and more widely distributed in the cases in which the object displayed before the phrase matched the noun in the phrase, but did not match the spatial configuration of the object described in the phrase. Figure 4.35, below, which shows topographic maps from the top-view of the head between 340 and 580ms post noun onset, offers a comparison across the scalp between

the two subtractions (between responses to nouns after spatially mismatching and matching pictures and to nouns after random objects and matching objects [in matching spatial configurations]).

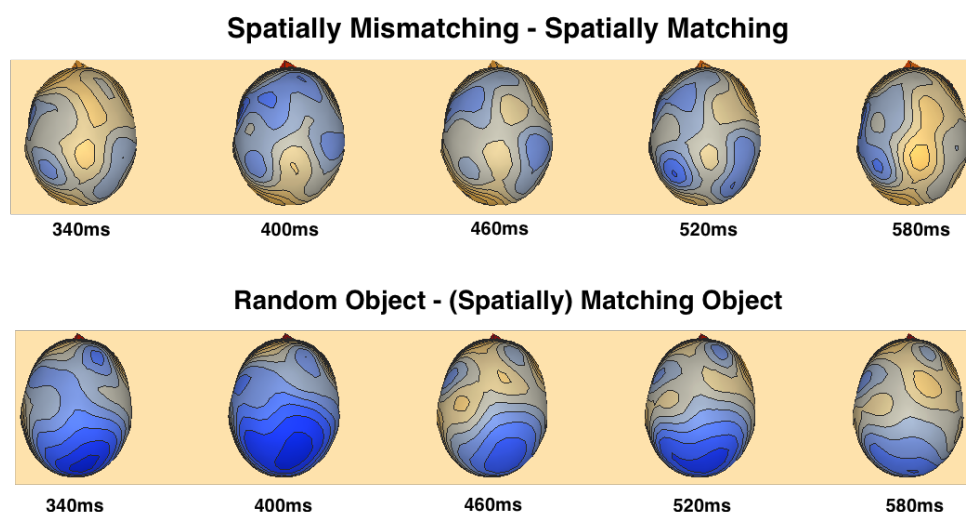
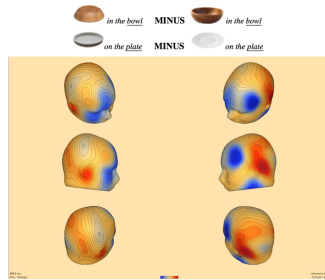


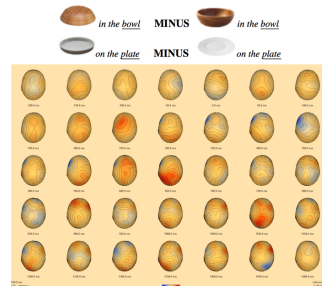
Figure 4.35: Resulting activity when responses to nouns after spatially matching pictures are subtracted from responses to nouns after spatially mismatching pictures (leaving the difference) and when responses to nouns after pictures of matching objects in matching spatial configurations are subtracted from responses to nouns after pictures of random objects.

The interaction between reference noun type (spatial match and spatial mismatch), the spatial configuration of the object shown in the picture before the phrase, and hemisphere had a marginally significant impact on voltage between 500ms and 650ms post-noun onset and a significant impact on voltage between 1050ms and 1250ms post-noun onset. This interaction reflected differences in the laterality and latency of the negativity (to nouns after seeing pictures of spatially mismatching objects) depending on whether the noun itself was predicted by the

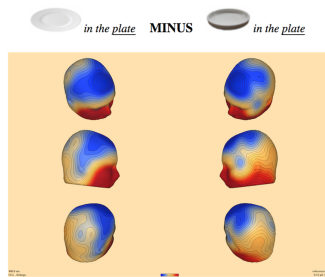
phrase. When the noun was predictable based on the spatial semantics of the preceding preposition (e.g., *in the bowl*), the relative frontal negativity caused by seeing a picture of an object in a spatially mismatching configuration (e.g., an upside-down bowl) was left-lateralized and dissipated by about 650ms post-noun-onset (See head maps in Figure 4.36a for subtracted responses at 400ms and in Figure 4.36b for responses across the averaging epoch). For the spatially unexpected nouns (e.g., *on the bowl*), the frontal negativity was bilateral and more broadly distributed and continued until the end of the averaging epoch (1500ms post-noun-onset) (See head maps in Figure 4.36c for subtracted responses at 400ms post-noun-onset and in Figure 4.36d for responses across the averaging epoch).



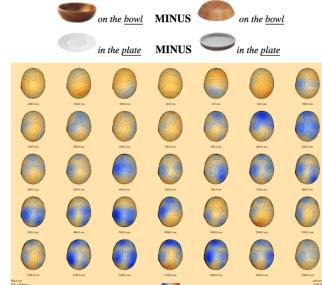
(a) Difference between voltage at 400ms post-noun-onset when responses to spatially matched nouns ("in the bowl"/"on the plate") after spatially matching pictures (e.g., an open-side-up bowl or a flat plate, respectively) are subtracted from responses to spatially matched nouns after spatially mismatching pictures (e.g., an open-side-down bowl or a concave plate, respectively)



(b) Difference between voltage when responses to spatially matched nouns ("in the bowl"/"on the plate") after spatially matching pictures (e.g., an open-side-up bowl or a flat plate, respectively) are subtracted from responses to spatially matched nouns after spatially mismatching pictures (e.g., an open-side-down bowl or a concave plate, respectively)



(c) Difference between voltage at 400ms post-noun-onset when responses to spatially mismatched nouns ("on the bowl"/"in the plate") after spatially matching pictures (e.g., an open-side-up bowl or a flat plate, respectively) are subtracted from responses to spatially matched nouns after spatially mismatching pictures (e.g., an open-side-down bowl or a concave plate, respectively)



(d) Difference between voltage when responses to spatially mismatched nouns ("on the bowl"/"in the plate") after spatially matching pictures (e.g., an open-side-up bowl or a flat plate, respectively) are subtracted from responses to spatially matched nouns after spatially mismatching pictures (e.g., an open-side-down bowl or a concave plate, respectively)

Figure 4.36: Responses to nouns after spatially matching pictures and spatially mismatching pictures for spatial match (top row) and mismatch (bottom row) nouns



#### 4.4.2.1.2 Abstract nouns

For reference nouns in abstract phrases (e.g., *in/on the know*, *in/on the mend*), effects of phrase type and picture were different than they were for the concrete phrases. Abstract nouns that did not match the previous preposition (e.g., *in the make*) did not yield an N400 effect when compared to abstract nouns that matched the preceding preposition (e.g., *on the make*). Compare the following figure, Figure 4.37, which shows the resulting waveform when responses to abstract match nouns are subtracted from responses to abstract mismatch nouns, to Figure 4.32 above.

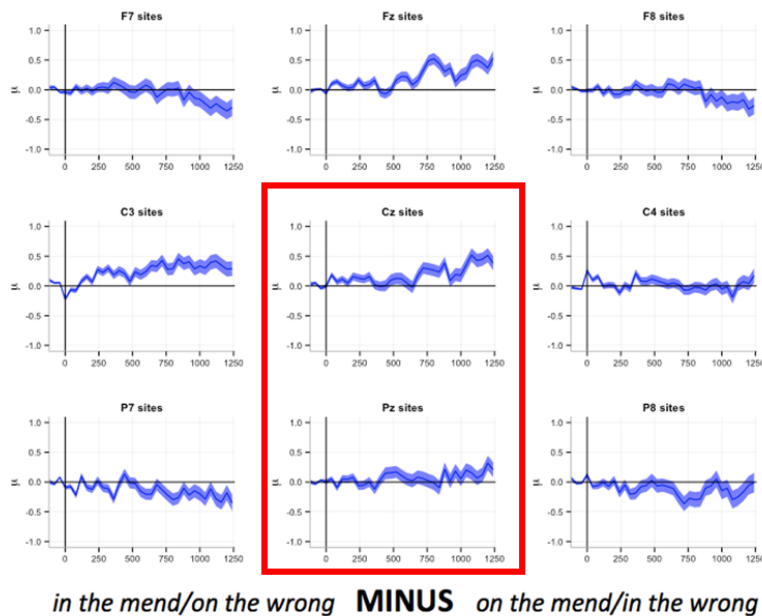
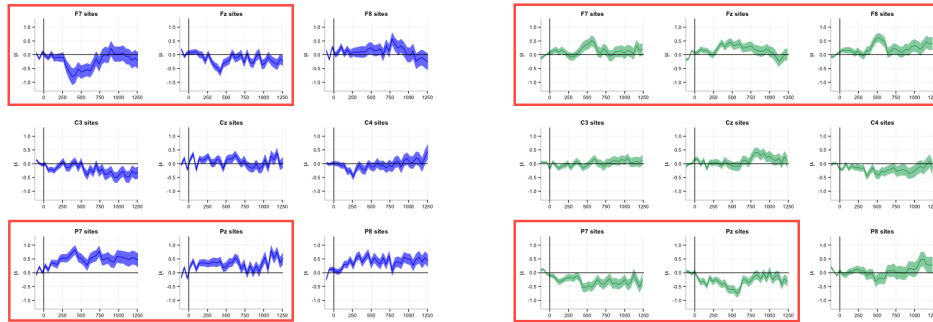


Figure 4.37: Subtracted responses between abstract mismatch nouns and abstract match nouns (abstract mismatch- abstract match) at nine regions selected from spatial PCA.

The only time window within which the comparison between responses to abstract match and mismatch nouns yielded a marginally significant difference (in interaction with the effect of hemisphere) started 1100ms after the onset of the noun. This result reflected a late positivity beginning about 1000ms post-noun onset in response to abstract mismatch phrases in medial posterior regions coinciding with a late negativity in lateral regions.

For abstract nouns, there was an effect of whether the spatial properties of the object in the picture displayed before the phrase matched the preposition (i.e., was a concave, container object more appropriate for *in* or a flat, surface object more appropriate for *on*). This effect was different from the frontal negativity and concurrent posterior positivity elicited by spatially matching and mismatching pictures for the concrete nouns. For abstract nouns, spatially mismatching pictures yielded a frontal positivity and concurrent posterior negativity, peaking at around 500ms post-noun onset. Compare regions highlighted in pink boxes in 4.38 to see that subtractions between responses to nouns after spatially mismatching and matching pictures show opposing polarity in posterior and frontal areas for concrete (left) and abstract (right) nouns.



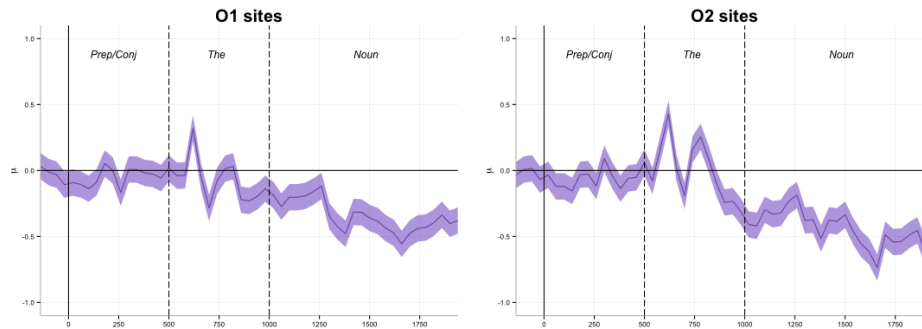
(a) Difference between voltage when responses to concrete nouns ("in/on the bowl") after spatially matching pictures (e.g., an open-side-up bowl for *in the bowl* or an open-side-down bowl for *on the bowl*) are subtracted from responses to concrete nouns after spatially mismatching pictures (e.g., an open-side-up bowl for *on the bowl* or an open-side-down bowl for *in the bowl*)

(b) Difference between voltage when responses to abstract nouns ("in/on the know") after spatially matching pictures (e.g., a concave, container-like object for *in the know* or a flat, surface-like object for *on the know*) are subtracted from responses to spatially mismatching pictures (e.g., a concave, container-like object for *on the know* or a flat, surface-like object for *in the know*)

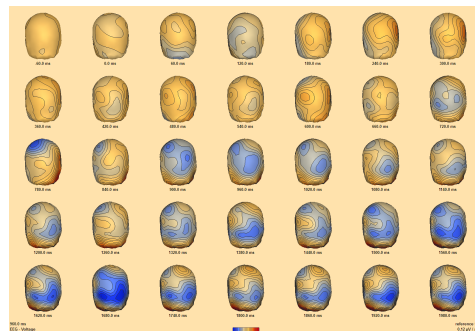
Figure 4.38: Subtraction of responses to nouns after spatially matching pictures from responses to nouns after spatially mismatching pictures.

#### 4.4.2.2 Responses to prepositions

Compared to non-spatial phrases headed by the conjunction *and*, spatial phrases headed by the prepositions *in* and *on* were more negative starting at about 800ms after the onset of the preposition (while *the* is displayed) in lateral occipital regions. This negativity was slightly larger in right occipital sites.



(a) Difference between voltage at left and right occipital regions when responses to conjunction phrases (*and the bowl/plate*) are subtracted from responses to preposition phrases (*in/on the bowl/plate*)



(b) Topoplots at the back of the head showing difference between voltage when responses to conjunction phrases (*and the bowl/plate*) are subtracted from responses to preposition phrases (*in/on the bowl/plate*)

Figure 4.39: Subtraction of responses to prepositional phrases from responses to conjunction phrases.

The type of object presented in photographs before the phrases impacted responses to prepositions from 300 to 500 milliseconds post-preposition onset, so that pictures of *in* objects resulted in smaller negativities at Cz to *in* and pictures of *on* objects yielded smaller negativities at Cz to *on*, no matter the configuration of the object in the picture. In other words, any picture of a bowl yielded decreased negativity to *in* compared to negativities after any picture of a plate did. This dif-

ference is not observable in ERPs to conjunctions, so that responses to conjunctions after seeing *in/on* objects were identical to responses to conjunctions after seeing pictures of objects that were neither a match for *in* nor *on*. See Figure 4.40 for responses to prepositions when the type of object shown in the picture either matched or did not match the preposition.

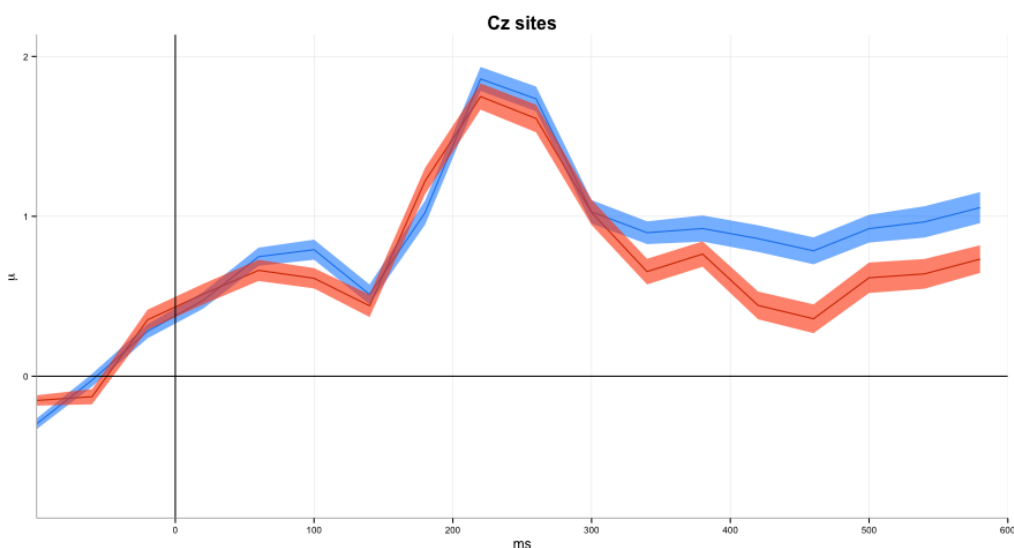


Figure 4.40: Responses to prepositions after pictures of objects whose type matches the preposition (blue), and after pictures of objects whose type does not match the preposition (red).

The effect of the object in pictures also impacted parieto-occipital slow-wave activity. There was a significant interaction between object-in-picture type and anteriority between 560 and 1000ms post-preposition onset, when the preposition was no longer on the screen and when determiner *the* was present instead. Prepositional phrases yielded relatively negative parieto-occipital slow-wave activity after

the presentation of pictures of random objects (objects that were neither matches for *in* nor *on*) and after the presentation of no picture. When prepositional phrases were presented after pictures of *in* or *on* objects (no matter their spatial configuration), parieto-occipital negativities were much smaller. See Figure 4.41, which shows subtracted responses to prepositional phrases in parietal regions after the presentation of pictures of random objects and no pictures and the after the presentation of spatially matching pictures.

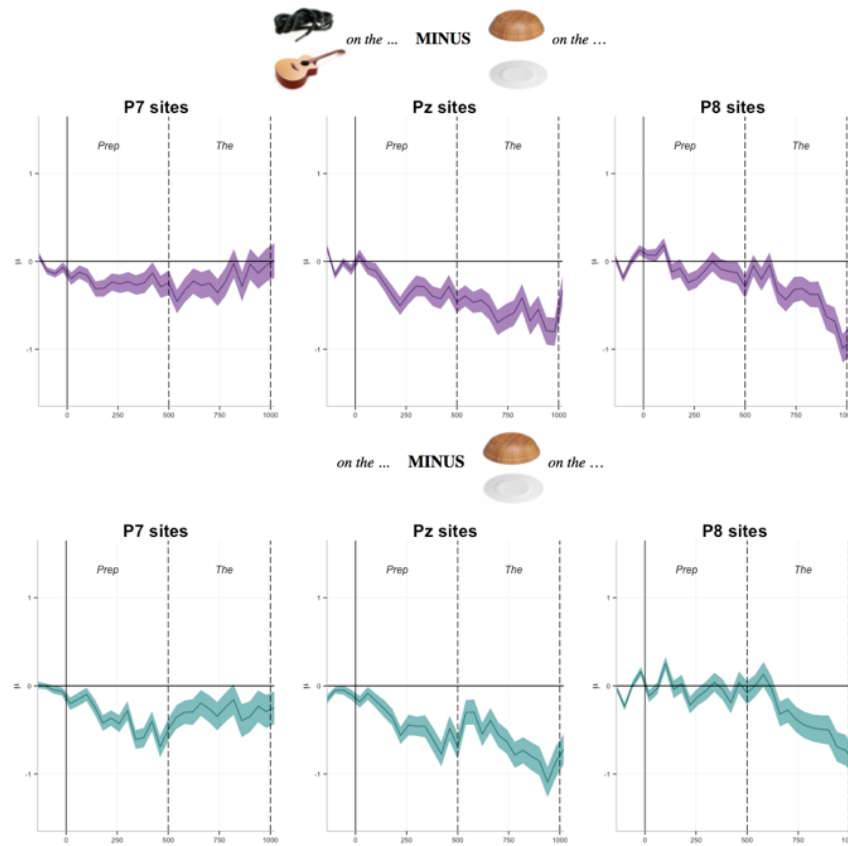
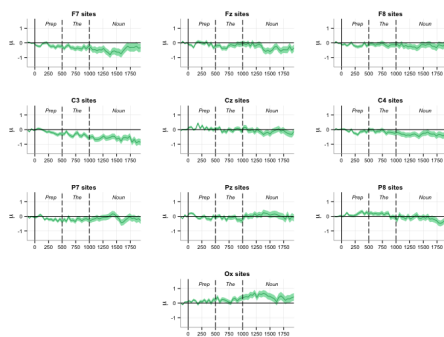


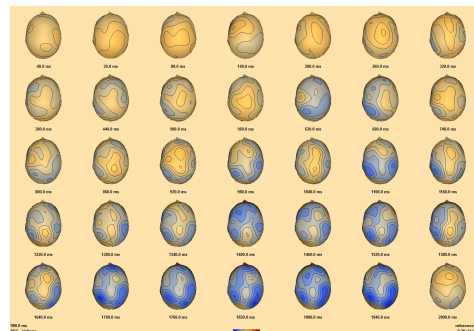
Figure 4.41: Subtracted responses in posterior regions between preposition phrases after random pictures (top) and no picture (bottom) and after spatially matching pictures.

The spatial configuration of objects also had a marginally significant effect on the processing of preposition phrases during this later time window (560ms-1000ms post-preposition onset). This marginally significant effect began after the offset of the preposition, i.e., the preposition was no longer on the screen and the definite determiner *the* was there instead. Spatially mismatching pictures yielded a left-lateralized negativity in frontal, central and parietal regions to prepositional

phrases, beginning at about 600ms post-preposition onset. This negativity continued for the next 1400ms, peaking during the time within which the noun was present on the screen, by which time the negativity was widely distributed, having spread to medial and right frontal regions (Fz and F8) and right central and parietal regions (C4 and P8).



(a) Resulting responses when ERPs to preposition phrases after spatially matching pictures (i.e., pictures of objects in *in* configurations before phrases headed by *in* and pictures of objects in *on* configurations before phrases headed by *on*) were subtracted from ERPs to preposition phrases after spatially mismatching pictures (i.e., pictures of objects in *on* configurations before phrases headed by *in* and vice versa for *on* phrases).



(b) Topoplots at the top of the head showing difference between voltage when responses to preposition phrases after spatially matching pictures (i.e., pictures of objects in *in* configurations before phrases headed by *in* and pictures of objects in *on* configurations before phrases headed by *on*) were subtracted from ERPs to preposition phrases after spatially mismatching pictures (i.e., pictures of objects in *on* configurations before phrases headed by *in* and vice versa for *on* phrases)

Figure 4.42: Subtraction of responses to prepositional phrases after pictures of spatially matching pictures from responses to prepositional phrases after spatially mismatching pictures.



## Chapter 5

### Discussion and Conclusions

*ERP results show that the N400 response and the parietal-occipital negativity were impacted by the visual depiction of objects and by the different linguistic materials used in concrete noun phrases. N400 effects to prepositions reveal that pictures of different types of objects are better or worse at priming the prepositions **in** and **on**, suggesting that an object's type plays a more crucial role in the lexical retrieval of prepositions than an object's configuration does. Downstream, N400 effects to nouns show that **in** and **on** are each better or worse at priming certain nouns. Spatial phrases yielded a late parieto-occipital negativity that was not elicited by non-spatial phrases. This response shows that the processing of simple spatial language activates the same neural networks in the parietal lobe that are implicated during non-linguistic spatial tasks, like mental rotation of an object. This negativity increased as imageability became more effortful, either because the phrase represented an unlikely spatial scene (e.g., **in the brick**), or because visual information did not correspond with the phrase. Further, there was an interaction between visual information and linguistic context on both the N400 response and parieto-occipital negativity, suggesting that the timing and type of integration of visual context is dependent on linguistic context. In general, results of this experiment reveal that reading and interpreting prepositional phrases is a complex, multifaceted and multi-modal process.*

## 5.1 Introduction

The current experiment examined: A) what ERPs are involved in the determination that an object is appropriate following a preposition; and B) how the visual depiction of objects impact ERPs elicited during the processing of spatial language.

With regards to the first research question, the results of this experiment supported the hypotheses that spatially mismatching nouns (e.g., *on the bowl*) would result in larger N400 responses than spatially matching nouns (e.g., *in the bowl*), and that prepositional phrases (*in/on the bowl*) would evoke relative negativities in parieto-occipital sites as compared to conjunction phrases (e.g., *and the bowl*). However, while it was predicted that spatially appropriate phrases *in the bowl* would yield increased parieto-occipital slow-wave activity as compared to responses to spatially inappropriate phrases *on the bowl*, the opposite result occurred, where spatially inappropriate phrases elicited increased slow-wave negativities.

With regards to the second research question about neural responses to spatial language dependent on visual context (photographs of objects), results supported the hypothesis that object type would modulate N400 activity to prepositions. For instance, N400 responses to the preposition *in* were relatively smaller when it was presented after pictures of *in* objects (e.g., bowls or buckets) than when it was presented after pictures of *on* objects (e.g., plates or mats). However, against prediction, N400 responses to prepositions were not affected by the visuo-spatial depiction,

tion of these objects (for instance, whether the pictures of bowls or buckets showed them upside down or right side up). Electrophysiological responses to reference nouns were indeed affected by the depiction of objects, but pictures of objects shown with spatially mismatching features and configurations yielded a frontal negativity rather than a traditional central parietal N400 response. The effect of the typicality of the object's depiction had no effect whatsoever on responses to nouns, against prediction. Finally, contrary to the hypothesis that parieto-occipital slow-wave activity would increase when spatial phrases followed pictures than when they did not, the opposite effect was achieved: Parieto-occipital negativity *increased* when spatial phrases were presented after no visual primes.

Below, these results are discussed further in relation to these hypotheses and the existing literature.

## **5.2 Discussion**

### **5.2.1 ERP responses modulated by spatial information**

As predicted, the timing and topography of ERP patterns revealed an N400 effect dependent on the spatial appropriateness of reference nouns. Increased negativity in medial central sites was elicited 325 milliseconds after the onset of nouns that were spatial/functional mismatches for the preceding preposition (e.g. *in the brick* and *on the bucket*). Several previous behavioral experiments, including the pilot

experiment for this study, described in Appendix A, have shown that the geometric and functional features of a reference object determine the acceptability of a prepositional phrase headed by *in* or *on* (Coventry and Prat-Sala 2001, Coventry et al. 1994, Feist and Gentner 1998, 2001, 2011), but, until now, no experiment has demonstrated that the connection between the semantics of prepositions and nouns is measurable in electrophysiology.

Numerous studies have shown that N400 responses to words in sentences show an inverse relationship between the word's predictability and the amplitude of the N400 response to that word: The more semantically predictable a word is in a sentential context, the lower the N400 response, suggesting that the lexical retrieval of a word is less effortful when the sentence it is presented in creates an appropriate semantic context for that word (Van Petten 1995, Van Petten et al. 1999, Federmeier and Kutas 1999, Hagoort and van Berkum 2007, Reviews in Federmeier and Kutas 1999, Kutas and Federmeier 2011, Lau et al. 2008, and Kuitunen 2007). In the current study, only the prepositions *in* and *on* were used to systematically vary semantic context in each phrase; the other words in the phrase were meaningless nonce words that were randomly assigned to the phrases (e.g., *floop*) and determiners, which provided no or very minimal semantic content. This meant that N400 modulation to nouns depended on the semantic features of the prepositions. This is the first study that has shown that prepositions can, on their own, create semantic priming effects measured by N400 amplitude.

It is possible that the prediction of shape features contributed to N400 effects,

so that the prepositions *in* and *on* each primed nouns whose referents were objects with particular shapes. For instance, nouns whose referents are typically flat (e.g., *plate*) may have been primed by *on* while nouns whose referents are concave (e.g., *bowl*) may have been primed by *in*. If so, this effect is similar to what was reported in Rommers et al. (2013), who discovered increased N400s to the final noun in a sentence when that noun's shape did not match the predicted noun. However, in the current study, shape features cannot have been wholly responsible for N400 effects to reference nouns, since the nouns that were included represented objects with a wide variety of different shapes. For example, *in* nouns included liquids (*coffee* and *milk*), concave objects (*bowl* and *bucket*), and objects with mutable shapes, depending on whether they are open or closed (*drawer* and *bag*). Therefore, it is likely that N400s to inappropriate reference nouns indexed the prediction/priming of myriad semantic features of nouns, including not only their shape, but also their functional properties. This provides support for theories of spatial language use and processing, like the functional geometric framework, which claim that object knowledge plays a key role in the choice of preposition to describe a spatial scene and in the way that prepositional phrases are interpreted (Carlson-Radvansky and Radvansky 1996, Carlson-Radvansky et al. 1999, Feist and Gentner 1998, Ferenz 2000, Coventry and Garrod 2004, Coventry et al. 2005).

Parieto-occipital slow-wave activity was relatively negative during the presentation of prepositional phrases as compared to responses to the presentation of conjunction phrases. This pattern was predicted based on previous research, like

Noordzij et al., which reported parieto-occipital slow-wave negativity evoked by spatial phrases (e.g. *the circle left of the triangle*), but not by matched, non-spatial phrases (e.g. *the circle and the triangle*) (2006). The two-dimensional geometric figures (circles and triangles) that were used as reference objects in their study have fixed shapes by definition; however, in the current study, reference nouns represented three-dimensional, real-world objects which have varying and mutable shapes (bowls, bags, sugar). Since similar slow-wave activity results from the processing of both types of spatial phrases, it seems that the neural processes used to interpret phrases involving *in* are equivalent no matter the spatial properties of the objects to which the preposition's spatial sense applies. This finding provides support for theories of spatial-language processing which posit that the spatial denotation for a preposition like *in* is underspecified and therefore flexible (Bennett 1968, Cooper 1968, Leech 1970, Miller and Johnson-Laird 1976, Talmy 1983, Herskovitz 1986, Landau and Jackendoff 1993). However, another interpretation for the same finding is that a preposition's denotation is not underspecified, but is instead *fully* specified, so that the central, or prototypical sense of a preposition is linked to multiple tertiary related senses; this network of senses exhaustively represents every sense of a preposition (Brugman and Lakoff 1988, Lakoff 1990, Tyler and Evans 2003, Lockwood et al. 2005, 2006, Lockwood 2009, Lipinski et al. 2012). The latter account is supported by the fact that even the abstract phrases used in this study (e.g., *in the moment*) showed relatively negative parieto-occipital slow-wave activity as compared to non-spatial phrases, suggesting that a single process is used to apply the denotation of a preposition to a phrase whether

the phrase is abstract or concrete. Underspecified definitions of prepositions, for instance " $x$  is located internal to  $y$ , with the constraint that  $x$  is smaller than  $y$ " for the preposition *in* (Leech 1970), cannot be applied to abstract phrases unless there is a process in place linking the core spatial meaning to abstract uses of it.

Parieto-occipital slow-wave negativity also provides support for theories which allege that the denotation of prepositions is imaginal (Brugman and Lakoff 1988, Lakoff 1990). Because this negativity has been associated with increased effort in the generation and manipulation of mental imagery during non-linguistic tasks (Bosch et al. 2001, Tadi et al. 2009, Lopez et al. 2011), Noordzij et al. (2006) conclude that parieto-occipital negativity elicited during spatial-language processing indexes the involvement of mental imagery (i.e., image schemas). This also suggests that the neural organization of spatial imagery is amodal or supramodal, so that verbal and sensory perception together feed a common spatial representation (Friederici and Levelt 1990, Landau and Jackendoff 1993, Bryant 1997, Barsalou 1999b,a, Cattaneo and Vecchi 2008, Struiksma et al. 2009). In this study, slow-wave amplitude was larger for spatially inappropriate or unexpected phrases like *in the brick* than it was for spatially appropriate/expected phrases like *in the bucket*; this shows that parieto-occipital slow-wave negativity increases as a function of increasing difficulty or effort in image formation, rather than heightened imageability. While this finding was not hypothesized (see Section 3.1.2, effects of visual information on the parieto-occipital slow-wave, discussed below, support this interpretation.

### 5.2.2 ERP responses modulated by visual information

N400 responses to prepositions were not impacted by whether the depiction of the object presented in the picture beforehand was spatially matching or mismatching. Instead, object type impacted N400 responses to prepositions, where pictures of *in* objects yielded smaller N400 responses to *in* and pictures of *on* objects yielded smaller N400 responses to *on*, no matter the configuration of the object in the picture. This suggests that any picture of a container object, like a bowl or bucket, primes *in* better than any picture of a plate will. There were similar N400 effects (larger N400s peaking at the same time and in the same electrodes) to both prepositions and conjunctions after no picture was presented; this helps to confirm that smaller negativities to prepositions after pictures of certain objects index priming effects, since it is impossible for priming to occur when nothing (no visual context) precedes the target word. Further, responses to conjunctions after the presentation of pictures of *in/on* objects were identical to responses after the presentation of pictures of objects that were neither a match for *in* nor *on*.

Therefore, pictures of *in/on* objects primed prepositions only, showing that the lexical retrieval of *in* and *on* is aided by pictures of certain types of objects. This result suggests that extraction of object information (its typical function, shape, etc.) from a visual scene plays more of a role in activating the lexical entry for a preposition than the particular visual features of that object in a specific context, providing support for models of spatial language which argue you that knowledge of object information is intrinsically involved in spatial language interpretation



and use (Coventry and Garrod 2004, Coventry et al. 2005, Carlson-Radvansky and Radvansky 1996, Carlson-Radvansky et al. 1999, Feist and Gentner 2011, 1998, Ferenz 2000).

The impact of object type in pictures on the processing of the prepositional phrases was observable downstream from the N400 response as well. As described in the previous section, prepositional phrases yielded relatively negative parieto-occipital slow-wave activity as compared to conjunction phrases. This difference is driven by the responses to prepositional phrases after the presentation of pictures of random objects (objects that were neither matches for *in* nor *on*) and after the presentation of no picture at all. When prepositional phrases were presented after pictures, specifically after pictures of *in* or *on* objects, parieto-occipital negativities were much smaller. This finding was exactly the opposite of what was predicted, based on the results reported in Noordzij et al. (2006).

Noordzij et al. reported larger parieto-occipital slow-wave negativity during the processing of spatial phrases when participants expected to connect the phrase's meaning to a visual scene than when they expected to compare the phrase's meaning to that of another phrase (2006). They interpret their findings as indicating more activation of spatial-image-formation processes during spatial-language comprehension when participants expect to associate spatial language to visual information. Also, Carlson et al. found increased parieto-occipital slow-wave activity to canonical pictures of objects in *above* and *below* configurations, suggesting that increased parieto-occipital slow-wave activity indexes increased imageability–

that is, when a visual scene more closely matches internal imaginal templates for a preposition's denotation, a clearer image is formed (2002).

If, however, increased parieto-occipital slow-wave is interpreted as indexing increased effort (and perhaps difficulty) in forming spatial imagery, it is not surprising that larger negativities were observed in the cases when preceding photographs depicted random objects whose shape, type, function, etc. were discordant with the spatial semantics of both *in* and *on*. In these cases, the visuo-spatial features of the previously-seen photograph were most difficult to incorporate with the semantics of the phrase, and therefore internal image-building processes had to work harder. Increased parieto-occipital negativity elicited by the cases in which the spatial semantics of the phrase was unexpected or inappropriate (e.g., *in the brick*), discussed in the previous section, further supports this interpretation.

A finding that is harder to account for is the relatively large parieto-occipital negativities elicited in the cases when *no* picture was presented before the phrase. Noordzij et al. (2006) found exactly the opposite response – increased parieto-occipital negativity when participants expected to connect linguistic information to pictorial information. They propose that their results reveal increased use of mental imagery when participants attempt to integrate linguistic information with visual information. One explanation for the contrasting findings of the current study and in those of Noordzij et al. (2006) hinges on the differences between the procedures of the two experiments. In Noordzij et al. (2006), phrases were presented before pictures, and then participants were asked to directly compare

visual scenes to spatial language. In the current study, phrases were presented *after* pictures, and participants were asked to recall the words of the phrase; this task required participants to hold each phrase in working memory. Possibly, participants used visual information to help them recall the phrases when they could. When they could not – in the trials in which visual information did not facilitate the processing and recollection of the phrases, either because the picture depicted a random object that had no connection to the words in the phrase or because there was no picture provided at all– participants relied on *internal*, spatial-image formation processes to scaffold their memory.

In summary, the relatively large parieto-occipital slow-wave negativities after no pictures and after pictures of random objects both support the same interpretation– that elevated slow-wave activity indexes increased effort in forming spatial imagery. The fact that the largest parieto-occipital negativities followed the largest N400 responses to prepositions suggests that the language-processing mechanisms responsible for semantic decoding and lexical access interact with those processes involved in forming spatial imagery during spatial-language processing. That is, in the cases when accessing the lexical entry of a preposition is more difficult because it is unprimed, spatial-image-building processes are increasingly activated.

While the spatial configuration of the object presented in the picture before the phrase did not impact N400 responses to *prepositions*, it did have a marginally significant impact on responses to *nouns* during the time that N400 effects might

be expected, between 340 and 620 milliseconds. However, the response patterns to nouns did not resemble traditional N400 effects. Instead, pictures of objects in spatially mismatching configurations elicited a frontal negativity to reference nouns in left and medial sites. The difference in scalp topography for this negativity and the negativity to spatially mismatching nouns (*in the plate*) suggests that these responses are distinct and that there are separable neural processes generating them.

An anterior negativity, with a similar peak latency has been reported in previous literature. Sometimes called a "frontal N400" or "anterior N400", it has been observed in paradigms comparing concrete nouns to abstract nouns, where N400 responses to concrete nouns are more anterior than N400s to abstract nouns (Kounios and Holcomb 1994, Holcomb et al. 1999, West and Holcomb 2000). Other studies have found that a frontal N400 is elicited as a response to pictures, and that its amplitude is increased when the picture is semantically incongruous, for instance when it is presented as an unrelated final frame in a visual narrative (West and Holcomb 2002, Cohn et al. 2012). West and Holcomb (2002) posit that the similar distribution of responses in these paradigms, and their similar sensitivity to task demands (e.g., an amplified response when participants are asked to focus on imagery) suggest that they index similar or identical functions, namely the amodal incorporation of "image-mediated" information into on-line semantic processing. Support for the fact that this frontal negativity relates to picture-to-word integration in the current study (where a larger response indexes an incongruity between pictures and language) comes from the fact that nouns presented after pictures of

random objects also elicited a frontal negativity (simultaneous to a centro-parietal N400 effect).

Because this frontal negativity was smaller when nouns were presented after spatially matching pictures, it seems that efforts to incorporate the information presented in the picture before the phrase did not only apply to the nouns themselves, but to the entire phrase. Incorporating the semantic information represented by a picture of a flat plate, for instance, to the processing of the noun *plate* should not be effortful. However, if the visual information (e.g., the shape of the plate) does not correspond with the semantics of the phrase in which the word *plate* is included (e.g., *in the plate*), then incorporation will be harder (West and Holcomb 2002, Cohn et al. 2012). It is exciting that such processes would be activated by the stimuli in this experimental paradigm, since participants were not instructed to integrate visual information with linguistic information; in fact, they were not instructed to focus on the visual information at all. The discovery that the visual depiction of objects modulated responses to nouns in this experiment shows that the incorporation of visual information into the on-line semantic representation of language is a relatively automatic process which occurs naturally.

Further, there were differences between this frontal N400, depending on whether the noun itself was appropriate for the preceding preposition, suggesting that the timing and type of integration of visual context is dependent on linguistic context. When the noun was primed by the preceding preposition (e.g., *on the plate*), the frontal negativity ended relatively early, as compared to the negativity to spatially

unexpected nouns (e.g., *in the plate*) when spatially mismatching pictures were shown beforehand. This pattern suggests that the processes involved in the integration of visual context were completed more quickly when the noun was primed by semantic context than when it was not, perhaps evidencing a less effortful process of visual-to-linguistic integration when a phrase is semantically felicitous. It is difficult to know whether this decreased effort is due to an inherent ease of processing in the case of semantically expected phrases, or to a decreased reliance on visual-to-linguistic incorporation when a phrase is semantically expected. Whatever the cause, this finding is similar to the response patterns for prepositions – when prepositions were unprimed by semantic (visual) context, processes involved in spatial-image formation were more effortful, leading to larger parieto-occipital negativity. The frontal negativity to nouns after spatially mismatching pictures was also more broadly distributed when the noun was unexpected, suggesting that more networks are recruited when both semantic *and* visual context are incongruous or unexpected. This shows that the semantic contribution of imagery can be extracted from both visual context (pictures) and language, so there is an additive effect in the frontal N400 response when both the picture preceding the phrase and the noun in the phrase correspond to images that are incongruous with the semantic representation of the phrase.

In summary, for both prepositions and nouns, ERPs reveal an interactive effect between linguistic priming effects and image-formation processes. When a word is primed, either by visual or linguistic context, there is decreased activation of visual-to-linguistic integration in the case of nouns and decreased involvement of

spatial-image formation in the case of prepositions. When a word is unprimed, image-related processes are increasingly implicated in order to scaffold linguistic processing.

### **5.3 Limitations**

The current task demands (asking participants to simply remember the phrases they read) were used so that ERP effects caused by visual and semantic information could be interpreted as representing natural and even sometimes subconscious processes that occur during on-line processing. Unfortunately, this task did not allow the results of the study to be directly comparable to previous literature which asked participants to compare phrases to pictures and asked participants to make semantic judgments about the phrases (Carlson et al. 2002, Noordzij et al. 2006). Further, some interpretations of the results– for instance, that increased slow-wave activity to prepositional phrases and increased anterior negativities to nouns implicate increased activity in image-processing networks– remain unsupported. Including differing task demands, perhaps asking participants to concentrate on pictures in some blocks and/or even having them make judgments about pictures or phrases, would have shown how increased attention to pictures and/or phrasal meaning impacted responses. This would have clarified some findings.

Improving features of the photographs used as stimuli in this experiment would also have helped to clarify findings, since aspects of the photographs may have

contributed to unexpected results.

Against predictions, for neither spatial match nor spatial mismatch nouns was there an N400 effect to nouns after the presentation of an atypical picture of an object. In fact, for spatial mismatch nouns, a slightly larger N400 response was elicited to reference nouns after the presentation of *typical* configurations of objects (See Figure E.4 in Appendix E). This is an odd result; however, since for spatial mismatch nouns, typical pictures were also ones for which the spatial configuration of the object did not match the preposition in the phrase, it is probable that the spatial configuration of the object contributed more to the negativity observed in medial central sites. In other words, for spatial mismatch nouns, the typicality of an object's depiction and the spatial configuration of an object's depiction were confounding variables, so that every atypical picture was a spatial match for these nouns and vice versa, every typical picture of an object was a mismatch for them. This meant that the influence of spatial factors (match vs. mismatch) and object typicality (typical vs. atypical) in pictures before spatial match nouns were re-categorizations of the same phenomena.

Therefore, only consistent responses across spatial match and spatial mismatch nouns after typical versus atypical pictures were considered to be real effects of typicality. Since there was no *consistent* N400 effect across spatial match and spatial mismatch nouns after atypical pictures, it appears that typical depictions of objects did not prime their labels more effectively than atypical ones did. While this at first seems to be a surprising result, the stimuli for this study were not



systematically designed to represent more or less typical versions of objects, and were instead designed to be better or worse matches for prepositions. For example, the noun *coffee* was included as an *in* object. The *in* version of the picture of that object was an open cup (a paper, disposable cup) of coffee, while the *on* version of the object was the same cup with a lid on top. The former was considered "typical" and the latter "atypical", but it is not clear that a closed cup of coffee is really atypical at all. In order to explore the effect of typicality more effectively, pictures should have been more carefully designed to do so.

Another prediction that was not borne out by the results of this study was an N400 effect to prepositions depending on the spatial features of the picture shown before the phrases. N400 responses to prepositions were not impacted by whether the picture was spatially matching or mismatching. As discussed above, this result suggests that knowledge of object type (its typical function, shape, etc.) plays more of a role in activating the lexical entry for a preposition than the visual features of an object in a particular context. However, a later examination into the different types of preposition phrases (those headed by *in* versus those headed by *on*) shows that the lack of an N400 response in the average was due to the lack of an N400-response for *in* phrases (see E). There is a fairly robust relative negativity in medial central and parietal regions (Cz and Pz) that peaks between 350-400ms after the onset of *on* after participants have seen a picture of an object in an *in* configuration (compared to responses after seeing pictures of objects in spatially matching, *on*, configurations). This is not true for *in* phrases. In fact, the opposite pattern occurs- so that responses to *in* is more negative in medial central

and parietal regions after seeing objects in *in* configurations.

This result- that a relative N400 response was elicited by reading *on* after seeing pictures of objects in *in* configurations, but not for the opposite case, when *in* was read after seeing pictures of objects in *on* configurations suggests that somehow *on* pictures were better at priming *on* than *in* pictures were at priming *on*. Differences between *in* and *on* photographs help to explicate this. For both *on* and *in* pictures, half of them were objects with features that are normally considered more appropriate for one preposition (e.g., a picture of a table for *on* or a picture of a bowl for *in*). The other half were of objects that are considered more appropriate for the opposite preposition, and were manipulated in some way so as to be considered more appropriate for the presented preposition. For instance, while the noun *table* (and its corresponding referent) is considered an *on* object (based on information like rating scores for *on the table* versus *in the table*), some versions/configurations of *table* can be considered more appropriate for *in*. In this experiment, a picture of a table with a drawer was used as the *in* version of the *on* object, *table*. See Figure 3.2 for examples of these manipulations.

For this second half of pictures – those of objects that were more appropriate for *in* or *on* but which were manipulated to be more appropriate for *on* or *in*, respectively– there was a difference between *in* and *on* pictures. Sixty percent (60%) of *in* versions of *on* objects were type manipulations, which meant that the pictures used showed completely different objects when the picture presented an *in* version versus an *on* version. For instance, the *on* object *table* was manipulated

into an *in* object by presenting a picture of a desk-like object with a drawer in it. Differently, 60% of *on* versions of *in* objects were configuration manipulations, so that the same object was used, but its configuration was altered. For example, the *in* object *bowl* was manipulated into an *on* object by showing it upside-down (with its open-side down on a surface).

Therefore, the type changes (which accounted for 30% of spatially matching pictures shown before *in*) may not have yielded as strong expectations for preposition choice as configuration changes (which accounted for 30% of spatially matching pictures shown before *on*) did. It is possible that type alterations primed multiple nominal labels (e.g., "table" and "desk" or "plate" and "dish"), which in turn muddied priming effects visible at the preposition. Future research can explore this difference by including an even distribution of type versus configuration manipulations across prepositions, so that responses to prepositions after different picture manipulations can be directly compared.

## 5.4 Future directions

### 5.4.1 Altering task demands

In order to better understand some of the findings from this study, a second iteration of the current study is proposed in which participants will be asked to perform different tasks. In some trials, participants will be required to directly

compare phrases to the visual stimuli. This manipulation will not only allow the results of the current study to be more directly comparable to some of the previous research, like Carlson et al. (2002) and Noordzij et al. (2006), but will also show whether asking participants to consciously focus on photographs increases the parieto-occipital slow-wave activity to prepositional phrases and the frontal N400 to reference nouns. If so, this will provide support for the current interpretation of findings– that increased slow-wave activity to prepositional phrases and increased anterior negativities to nouns both reveal increased efforts in image-related processes.

#### **5.4.2 Participants with Autism Spectrum Disorder**

It is well documented that the acquisition of language in many children with Autism Spectrum Disorder (ASD) is delayed compared to typically developing children, and that once children with ASD have acquired language, their language use and interpretation can be unusual (Tager-Flusberg et al. 2005). Beginning with Kanner et al.'s seminal work which first identified and described the condition (1943), it has been reported that children with ASD show particular deficits in spatial term use and understanding (See, for example Paul et al. 2004 and McGee et al. 1985). For this reason, instructing children with ASD on appropriate preposition use has been an area of particular focus in language therapy and intervention (See review in Goldstein 2002).

Delayed acquisition and/or differences in prepositional usage and understand-

ing in children with ASD might be explained by the polysemous and abstract nature of prepositions' denotations. As shown in this study, the meaning of prepositions is multifaceted and relies on knowledge about object information. Further, prepositions are used metaphorically, in abstract phrases like *in the moment*. This project has also shown that the processing of spatial language likely relies on multimodal resources, requiring language-processing areas of the brain to connect to other networks, like those involved in spatial-image formation, object knowledge/understanding, and visual processing. Research has suggested that the brains of people with ASD show fewer long-distance neural connections (Review in Rane et al. 2015). Therefore, there may even be neural explanations for disordered or limited prepositional use and understanding.

A follow-up study will recruit a group of high-functioning children with ASD to participate in the current protocol. This population is selected since high-functioning children are likely to have well-developed language skills and will therefore be able read the phrases presented and to understand task questions. While these children are predicted to show typical (or near-typical) prepositional understanding and use on standardized measures, it is predicted that their ERP responses will evidence relatively low (as compared to their typically developing peers) recruitment of image-related neural networks, as measured by the amplitude of parieto-occipital slow-wave activity to prepositions and frontal negativity to nouns. It is also predicted that picture type will have a decreased impact on N400 responses to prepositions (and nouns). Both of these results would provide support that these children rely less on multi-modal information to process spatial language. which

would not only help to explain deficits in prepositional use by children with ASD, but would also provide support for the "Weak Central Coherence" explanation for the symptomology of people with ASD, first presented in Frith (1989).

### 5.4.3 Second-language participants

It is well known that prepositions are especially difficult for English language learners to acquire successfully (Lorincz and Gordon 2013). One explanation for their difficulty with English prepositions is that their native language maps perceptible spatial information to spatial words differently than English does. In Spanish, for example, a single preposition, *en*, encompasses the concepts that the two English prepositions *in* and *on* separately represent. Unsurprisingly, Spanish speakers learning English frequently make errors when they use English *in* and *on* to describe spatial scenes (Cronnell 1985, Antrim 2008, Lindstromberg 2010).

The results of the current experiment provide a picture of the underlying neural processes by which an English speaker's brain processes spatial language and associates visual information with spatial language. Results show that the processing of spatial phrases including *in* and *on* likely involves general, extralinguistic cognitive processes, like mental image formation and knowledge about the typical way that objects function and interact with one another in the world. This suggests that speakers of languages that do not make a linguistic distinction between the concepts represented by *in* and *on* in English (e.g., Spanish speakers) will nevertheless be sensitive to the imaginal and functional features that these prepo-

sitions represent. The results of the current study provide a baseline by which one can compare developing neural associations between visual information and spatial language in ELLs. A future goal will be to recruit groups of native-Spanish-speaking ELLs with varying degrees of fluency in English, in order to examine how perceptual experience of objects versus linguistic experience modulate processing of prepositional phrases in English as speakers gain fluency.

## 5.5 Conclusions

Cortical potentials elicited by spatial phrases in this experiment suggest that the processing of spatial phrases involves the activation of brain mechanisms implicated during the processing of general spatial information. While this finding has already been reported in an ERP study of the processing of spatial language, it has never been achieved in a study that includes spatial phrases describing three-dimensional, real-world objects.

In fact, ERP results reveal a strong connection between preposition meaning and real-world object knowledge/semantics. The presentation of the prepositions *in* and *on* each activated the lexical entries for different types of nouns. For instance, the preposition *on* more effectively primed nouns that represented flat objects used as surfaces (e.g., "plate") than it did concave objects used as containers (e.g., "bowl"), and vice versa for *in*. As described in the discussion, prepositions likely predict/prime myriad semantic features of nouns, including not only their shape,

but also their functional properties and their make-up, since the nouns used in this study represented objects of all sorts. This result, along with the sentence-rating results from the pilot study, provide evidence that prepositions modulate semantic expectations and/or ease of retrieval for upcoming words during on-line sentence processing just as open-class words do. All closed-class words may be able to do this; however, it is more probable that prepositions are special, falling somewhere in between closed- and open-class words in terms of their role in the lexicon and in terms of their ability to activate the semantic representation of other words. Prepositions' close semantic relationship to nominal semantics (since the denotation of a preposition is inextricably associated with object-to-object configurations) entails that the activation of a preposition's lexical entry will co-activate nouns that represent concordant object types. Therefore, it is probable that prepositions are able to activate the lexical semantics of upcoming nouns when other closed-class words cannot, or, at least, cannot do so as effectively. Further research should explore whether other closed-class lexical items are capable of modulating N400 responses to upcoming words, and also to see whether prepositions which have an arguably weaker semantic representation (e.g., *of*) can do so as well.

The early timing of N400 effects to inappropriate concrete nouns after prepositions, beginning at 325ms post-noun onset, suggests that the processes involved in incorporating the semantic representation of concrete nouns with that of the preceding preposition is a relatively rapid, perhaps automatic process. In contrast, differences between ERPs to inappropriate and appropriate abstract nouns after prepositions (e.g., "on the moment" and "in the moment", respectively) begins



much later, 700ms post-noun onset, suggesting that a separate, less automatic and perhaps grammatical (syntactic) process is involved in decoding and processing abstract uses of prepositions.

While the denotations of prepositions do not correspond directly to sensory information (i.e., one cannot see, touch or hear *in*), the results of this study reveal that the depiction of information perceived visually (objects in photographs) affects the way the brain processes prepositional phrases. When photographs of three-dimensional, real-world objects were shown prior to the presentation of prepositional phrases, ERP responses to these phrases varied, depending on whether the spatial features and configurations of the objects in the photographs matched the spatial information represented by the phrase. This supports an interactive network between the visual processing of real-world objects and spatial-language processors. This process was evidenced even though task demands did not require integration between picture and language information, suggesting that the on-line incorporation of visual information into the semantic representation of a spatial phrase is a passive procedure that occurs naturally. Further, the relatively early timing of negativities after prepositions that did not match the preceding picture, starting approximately 300ms after the onset of the preposition, suggests that this procedure is automatic.

Increased negativity in parieto-occipital sites was observable for all the spatial phrases (as compared to the non-spatial, conjunction phrases), which suggests that the neural mechanisms involved in processing spatial language likely rely on

abstract, amodal spatial templates and imagery, which are accessed and/or updated on-line based on input from visual information and from language. The fact that the largest parieto-occipital slow-waves were elicited by the same trials which elicited the largest N400 response suggest an interactive network between linguistic-priming and image-formation processes. When a word is primed, either by visual or linguistic context, there is decreased activation of visual-to-linguistic integration in the case of nouns and decreased involvement of spatial-image formation in the case of prepositions. When a word is unprimed, image-related processes are increasingly implicated in order to scaffold linguistic processing. This reveals that reading and interpreting simple prepositional phrases involving real-world objects involves the integration of visual information, object information, and spatial information on line. More broadly, this study's findings suggest that the processing of *all* language, even simple phrases containing words that are believed to have limited semantic content, engages a multifaceted neural network that involves linguistic and non-linguistic representations.

# Appendix A

## Pilot Experiment

*A sentence-rating experiment was implemented to test the materials that would later be used in the ERP experiment. Sentence rating scores were collected to get people's conscious perception of the phrases that were designed for the ERP experiment. Sentence reading- and rating-times were also measured, to see if sentence- and picture-type affect people's processing of these phrases, with the expectation that slower reading and rating times would suggest more arduous processing. It was found that phrase type (but not picture type) significantly affected rating scores, and that the interaction between phrase type and picture type significantly affected reading and rating times. This chapter presents the methods and results of this experiment and explains how its results inform predictions for the ERP study.*

## A.1 Introduction

Before running the ERP experiment, a sentence-rating experiment was designed and completed in order to test:

1. Whether the type of reference object used in a prepositional phrase affects people's perception of spatial sentences;
2. Whether the visual depiction of these reference objects implicitly affects people's perception of spatial sentences.

While previous studies have found that the spatial and functional properties of reference nouns determine whether people accept/produce them after *in* or *on*, most of these studies used a small set of reference objects (Coventry 1993, Coventry et al. 1994, Coventry 1999, Coventry and Prat-Sala 2001, Coventry et al. 2010, Feist and Gentner 1998, 2001, 2011). Because ERP experiments require many trials, it was necessary to come up with a list of at least ten different reference objects for each preposition, *in* and *on*. The sentence-rating scores collected in this pilot experiment helped to confirm whether the reference nouns chosen for the ERP experiment are significantly more acceptable after the preposition *in* or *on*, respectively. Further, previous research has shown that the visual depiction of an object's spatial properties explicitly affects the acceptability of the name for that object to be used with *in* and *on* (Feist and Gentner 2011), but no research has shown that the visual depiction of spatial properties can affect processing of spatial language (as is predicted to occur during the ERP study). Reading and

reading times in the sentence-rating experiment will show whether the visual depiction of objects implicitly impacts the processing of spatial sentences. In short, the sentence-rating experiment was used to help to test the materials that would eventually be used in the ERP experiment (described in Chapter 3) and helped to inform predictions for the ERP experiment's results.

## **A.2 Methods**

### **A.2.1 Participants**

Sixteen English speakers participated in this study (M=25 years, 9 females). Of these sixteen participants, fifteen were native English speakers. One began learning English at age 5, when she moved to the United States. Thirteen participants were born in the United States, one was born in Russia, one in India, and one in Canada. All participants had graduated from high school and were either pursuing an undergraduate or graduate degree. Most participants spoke a second language. These languages included Spanish, Italian, Hebrew, Yiddish, Hindi, Punjabi, Urdu, Arabic, Japanese, Russian and French.

Recruitment for the study was accomplished by posting flyers around the CUNY Graduate Center, at coffee shops near other universities and via personal referral. IRB approval (protocol # 11-11-336-0135) was granted by the CUNY Graduate Center and all participants signed an informed consent form (See Appendix).

## A.2.2 Stimuli

### A.2.2.1 Sentences

Linguistic stimuli consisted of 204 sentences. All phrases fit the following frame:

There is the Located OBJECT PREP/CONJ the Reference OBJECT

In all of the sentences, the located object is a nonce word and the reference object is a real word (e.g., *there is the flep in the bowl; there is the flep and the bowl*).

A nonce word was used as the located object in each sentence in order to minimize its contribution to the semantic representation of the sentence. Located objects were selected from a list of 33 monosyllabic nonce words (e.g., "toose" and "wid"). The biphone and phoneme-position probabilities of the sounds in these words were calculated using the Vitevitch phonotactic probability calculator and were controlled to match the variation in real, monosyllabic English words<sup>1</sup> (Vitevitch and Luce 2004).

Each reference noun (see Chapter 3, Section 3.3.2.2 for a description of how the concrete and abstract nouns were selected) is presented after the prepositions *in* or *on*. The non-spatial sentences were constructed using the conjunction *and* followed by the reference objects from the spatial match and control conditions.

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<sup>1</sup>These nonce words were initially designed to be used in a study measuring language processing in typically developing children and in children with Autism Spectrum Disorders between the ages of 3 and 11 years. As such, the words were constructed to match the variation of real English words which are familiar to children of these ages (Hawkland et al. In Press).

There were 24 (12 *in*/12 *on*) sentences of each type of prepositional phrase and 60 conjunction phrases.

The sentences included in the study were of eight types:

1. **Spatial Match:** *There is the flep in the bowl/There is the flep on the plate*
2. **Spatial Mismatch :** *There is the flep on the bowl/There is the flep in the plate*
3. **Spatial Neutral:** *There is the flep in/on the box*
4. **Abstract Match:** *There is the flep in the moment/There is the flep on the verge*
5. **Abstract Mismatch:** *There is the flep on the moment/There is the flep in the verge*
6. **Ungrammatical:** *There is the flep in/on the ran*
7. **Non-Spatial Match:** *There is the flep and the bowl/plate/box*
8. **Non-Spatial Control/Filler:** *There is the flep and the button/apple/guitar*

#### **A.2.2.2 Visual stimuli**

The photographs are all presented on a white background. The photographs are either from Google images or taken by the author. Most of the objects are depicted on a white backdrop. When this type of photograph was unavailable, the picture is edited so that background information is minimally distracting. For the concrete nouns used in prepositional sentences (spatial match, mismatch and neutral) and in non-spatial control sentences, two different versions of the objects were displayed: an *in* version vs. an *on* version. *In* and *on* versions of each object was created

by manipulating various features of the objects, including the object’s geometric shape, the object’s configuration, and/or the object’s type:







OBJECT	MANIPULATED FEATURE	<i>IN</i> VERSION	<i>ON</i> VERSION
<i>bowl</i>	configuration		
<i>plate</i>	shape		
<i>table</i>	type		

Figure A.1: Example photographs of concrete objects for pilot experiment

For the abstract and ungrammatical sentences, pictures of objects without obvious labels were used. These objects were designed to represent either an *in* or an *on* configuration (see table 3 for examples). Six photographs of *in* objects and six photographs of *on* objects were created.

IN object	ON object
	
	

Figure A.2: Example photographs of abstract objects

For the conjunction sentences used as controls/fillers, these two pictures simply displayed different tokens of the same type, e.g. a green and a red apple or an



electric and an acoustic guitar.

### **A.2.2.3 Auditory stimuli**

A tone is played before 25% of the items, when no visual (photographic) stimulus is presented. The tone is a single "Ping" sound selected from the built-in sound effects from a Macintosh OS X, Version 10.9.3. The tone was edited in Adobe Audition so that it lasted for 500 milliseconds.

### **A.2.2.4 Item types**

Four possible stimuli precede each sentence with a preposition in it. Because there are 204 sentences, there are 816 items in total. Each sentence is preceded by one of the four following stimuli:

1. One of three photographs:
  - a. A photograph of an object, whose configuration matches the preposition in the sentence
  - b. A photograph of an object, whose configuration does not match the preposition in the sentence
  - c. A photograph of an unrelated object
2. No photograph and an auditory tone

For the concrete prepositional phrases (space match, space mismatch, and , the three photographs are of: 1) A spatially matching picture of the object in the phrase; 2) A spatially mismatching picture of the object in the phrase; 3) A random, unrelated object. See Figure A.3 for









Spatial Match: <i>there is the flep on the plate</i>		Spatial Mismatch: <i>there is the flep in the plate</i>	
No Picture		No Picture	
Object Match, Spatial Match		Object Match, Spatial Match	
Object Match, Spatial Mismatch		Object Match, Spatial Mismatch	
Object Mismatch		Object Mismatch	

Figure A.3: Example items for the concrete spatial sentences *there is the flep on the plate* and *there is the flep in the plate*

For the abstract spatial sentences and the ungrammatical sentences, the three photographs are of: 1) A spatially matching picture of an object without an obvious label; 2) A spatially mismatching picture of an object without an obvious label; 3) A random, unrelated object. See Figure A.4 for example photographs for *there is the flep in the afternoon* and *there is the flep on the afternoon*.

For the non-spatial sentences that act as matches for the spatial sentences (e.g., *and the plate*), the three photographs are of: 1) the *in* version of the object; 2) the *on* version of the object; 3) a random, unrelated object. For the conjunction phrases that act as control/filler phrases for the study (e.g., *and the string*), the three photographs are of: 1) one version of the object; 2) a different version of the









Abstract Match: <i>there is the flep in the afternoon</i>		Abstract Mismatch: <i>there is the flep on the afternoon</i>	
No Picture		No Picture	
Object Mismatch, Space Match		Object Mismatch, Space Match	
Object Mismatch, Space Mismatch		Object Mismatch, Space Mismatch	
Object Mismatch		Object Mismatch	

Figure A.4: Example items for the abstract sentences *there is the flep in the afternoon* and *there is the flep on the afternoon*

object; 3) a random, unrelated object. See Figure A.5 for examples for *there is the flep and the plate* and *there is the flep and the guitar*.









Control: <i>there is the flep and the plate</i>		Filler: <i>there is the flep and the guitar</i>	
No Picture		No Picture	
Object Match 1: <i>In Version</i>		Object Match 1	
Object Match 2: <i>On Version</i>		Object Match 2	
Object Mismatch		Object Mismatch	

Figure A.5: Example items for the non-spatial sentences *there is the flep and the plate* and *there is the flep and the guitar*

#### A.2.2.5 Lists

The full list was divided into four lists of 204 items. These smaller lists were designed so that a list did not repeat the same sentence, nor did it show the same

picture of concrete objects twice. Unfortunately, there were fewer pictures of abstract objects, which meant that each list repeated pictures of abstract objects 3 times. These four lists were then randomly split into two lists of 102 items. A random number generator from the Internet was used to create the presentation order for each list.

#### A.2.2.6 Rating task

Participants are asked to rate each sentence on its level of "surprise". This level based on how unexpected or unlikely the scene described in the sentence is. They are told to base their ratings on the sentences alone, i.e., not on the preceding photographs. The rating scale, on which participants pick a rating score, is a number line from 0 to 4. The scale is semi-continuous, so that participants can select a point at a tenth of the number line.

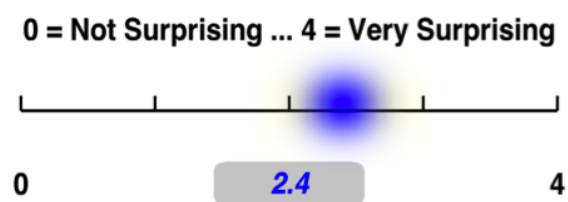


Figure A.6: Rating scale for sentence rating experiment

Once participants click a portion of the line, the corresponding rating score is displayed on a gray button below the line (e.g. "2.4" in Figure A.6). When participants are satisfied with their rating, they click the gray button in order to continue. This method ensures that the cursor arrow would always return to the same, lower,

central portion of the screen at the end of each rating session.

### **A.2.3 Procedure and presentation**

A Macintosh OS X laptop (Version 10.9.5) laptop was placed on a table in a quiet room, and participants sat in a chair positioned at this table. After each participant had signed the consent form, the experimenter briefly explained the procedures to the participant and then fitted headphones on the participants ears. Once they were ready to begin, the experimenter started up a practice session.

In the practice session, participants were presented with six items (pictures or tones followed by sentences), which gave them a sense of the types of sentences they would see and got them comfortable with the rating scale. The sentences used in practice did not contain any of the prepositions, conjunctions or reference nouns used in the experimental items. During the practice portion, participants received feedback after each rating, e.g. "The sentence 'there is a flep under the walked' should have received a rating between 3 and 4 since this is an unlikely sentence." When the practice session was complete, participants were prompted to ask any questions they had and to continue on to the experimental items when they were ready.

The procedure for the experimental items was the same as for the practice session except that no feedback was provided in the case of the practice sessions. The experimenter stayed in the room with the participant during the instructions and

the preliminary practice session. After the practice session, the experimenter left the participant alone so that s/he could concentrate fully on the study.

All materials (practice and experimental) were presented to participants using PsychoPy Software (Version 1.81.00) (Peirce 2007). As described in Section A.2.2.4, each item began with either a photograph or an auditory tone presented alongside a blank white screen. Photographs were displayed in the center of a white background on the laptop's screen for 500ms before each sentence began. The auditory stimulus was presented for 500ms through a pair of headphones, while a plain white screen was displayed. After the photo/tone ended, a fixation cross was displayed for 500ms. The sentence was displayed all at once, in the center of the screen, in Arial font. Participants read the sentence and pressed "spacebar" when they were ready to rate the sentence. Participants were instructed to read at their own pace, i.e., they were not instructed to go as quickly as possible. Once they pressed "spacebar", they were presented with the rating scale and selected a score by moving the bar to the corresponding rating on the number line, using the laptop's touchpad.

#### **A.2.4 Analysis**

Sentence ratings were recorded and averaged by category (sentence type, picture type, etc.). Sentence reading and rating times were also measured. For each participant, their reading and rating time was converted into a normalized score- the number of deviations from the median.

All statistical analyses were performed in R. A linear mixed model was run on all three dependent measures. The independent variables compared were sentence type and picture type. Picture type was split into two categories: whether the picture's features matched the preposition and whether the picture matched the object in the sentence. Each independent factor was added to the model, and these models were compared using an ANOVA in order to find the "best" fit. The slopes were varied by the intercept of participant, so that variations in reading and rating scores attributable to individual differences were ignored.

For some analyses, only a subset of the data was considered. For instance, ungrammatical *in the ran* and idiomatic *in the red* sentences were never presented after a picture that matched the object in the sentence. Therefore, when determining whether the picture matched the object made an impact on dependent variables, idiomatic and ungrammatical sentences were excluded from the analysis, since they were always mismatched. The conditions included in each analysis are provided in the results section.

### **A.3 Results**

Figure A.7 displays the results of the ANOVA comparing different models. Data are also displayed in graphs in the following subsections , but only when differences are significant.

Dependent Variables	DATA SET	RATING SCORE	READING TIME	RATING TIME
<b>Sentence Type (Compared to null)</b>	All items	<b>*p&lt;2 e-16</b>	<b>*p=6.659 e-6</b>	<b>*p=1.041 e-8</b>
	Experimental items (not fillers)	<b>*p&lt;2 e-16</b>	p=.3645	<b>*p=9.996 e-4</b>
	Concrete items (not idiomatic or ungram)	<b>*p&lt;2 e-16</b>	<b>*p=0.004006</b>	<b>*p=2.345 e-6</b>
<b>Picture Match Preposition (Compared to null)</b>	All items	NA	NA	NA
	Experimental items (not fillers)	p=.7577	p=.9040	<b>*p=.014086</b>
	Concrete items (not idiomatic or ungram)	NA	NA	NA
<b>Picture Match Object (Compared to null)</b>	All items	NA	NA	NA
	Experimental items (not fillers)	NA	NA	NA
	Concrete items (not idiomatic or ungram)	p=.2041	<b>*p=.01367</b>	p=.2014
<b>Sentence Type + Picture Match Preposition (Compared to sentence type as only explanatory variable)</b>	All items	NA	NA	NA
	Experimental items (not fillers)	p=.5358	p=.8985	<b>*p=.0123</b>
	Concrete items (not idiomatic or ungram)	NA	NA	NA
<b>Sentence Type + Picture Match Object (Compared to sentence type as only explanatory variable)</b>	All items	NA	NA	NA
	Experimental items (not fillers)	NA	NA	NA
	Concrete items (not idiomatic or ungram)	p= 0.1281	<b>*p=.01304</b>	p=0.1854

Figure A.7: Results of mixed model. Significant results are in bold.

### A.3.1 Sentence Type

Sentence type significantly affected all three dependent factors, when this model was compared to a null model: Rating score ( $p < 2.0 \text{ e-}16$ ), reading times ( $p = 6.66 \text{ e-}6$ ) and rating times ( $p < 0.01 \text{ e-}5$ ). For the experimental sentences (those with prepositions), sentence type significantly affected rating scores ( $p < 2.0 \text{ e-}16$ ) and rating times ( $p < 0.001$ ), but not reading times ( $p = 0.36$ ). And for the concrete sentences (those that described spatial or non-spatial configurations between real-



world objects), sentence type again affected all three dependent variables: rating score ( $p < 2.0 \times 10^{-16}$ ), reading times ( $p < 0.01$ ) and rating times ( $p < 0.01 \times 10^{-3}$ ). See Table A.1 for a list of mean rating times, normalized reading times and normalized rating times. And see Figure A.8 and A.9 to see graphical representations of mean rating scores and reading/rating times, respectively, with error bars reflecting the standard error of the mean.

Sentence Types	Mean Rating Score	Mean Normalized Read Time (Deviations from Median)	Mean Normalized Rate Time (Deviations from Median)
Non-Spatial Match	0.526	0.039	0.261
Space Match	0.504	0.230	0.498
Neutral Match	0.669	0.294	0.799
Abstract Match	1.668	0.494	0.949
Space Mismatch	1.693	0.370	0.941
Abstract Mismatch	2.988	0.493	0.611
Ungrammatical	3.495	0.196	0.193

Table A.1: Mean rating times, normalized reading time and rating times by sentence type.

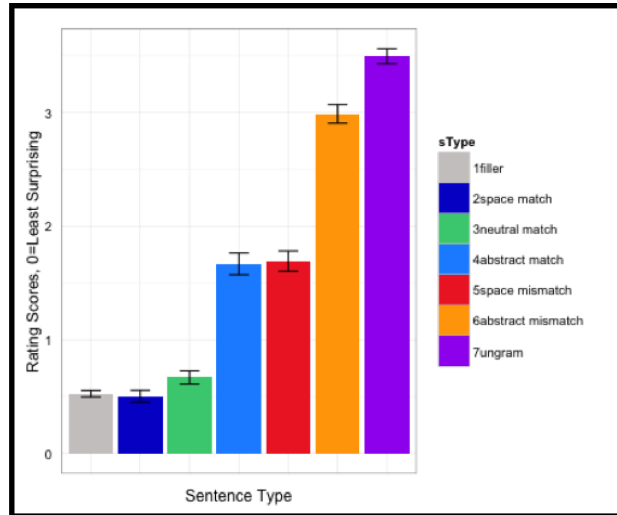


Figure A.8: Rating scores by sentence types

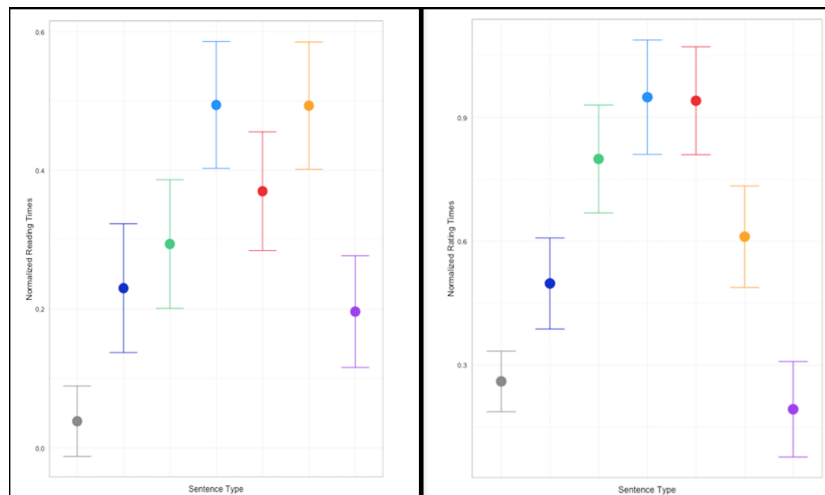


Figure A.9: Left: Normalized reading times by sentence types; Right: Normalized rating times by sentence types

### A.3.2 Picture Type

Whether the picture matched the preposition significantly affected rating times ( $p < 0.02$ ) (see Figure A.10), but not reading times or rating scores. Only experimental conditions were included in this analysis: space match, space mismatch, space control, abstract match, abstract mismatch and ungrammatical. Conditions excluded: non-spatial controls/fillers and matches.

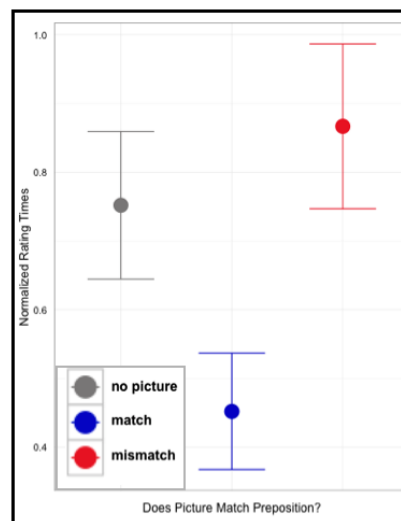


Figure A.10: Normalized rating times by picture type, whether the visual depiction of the object shown before the sentence matches the preposition in the sentence

The best model for the rating times for the experimental items was one that combined both sentence and picture type (whether the picture matched the preposition). This model was significantly better than sentence type or picture type alone ( $p=0.0123$ , when compared to the model that just used sentence type to explain rating-time variance).

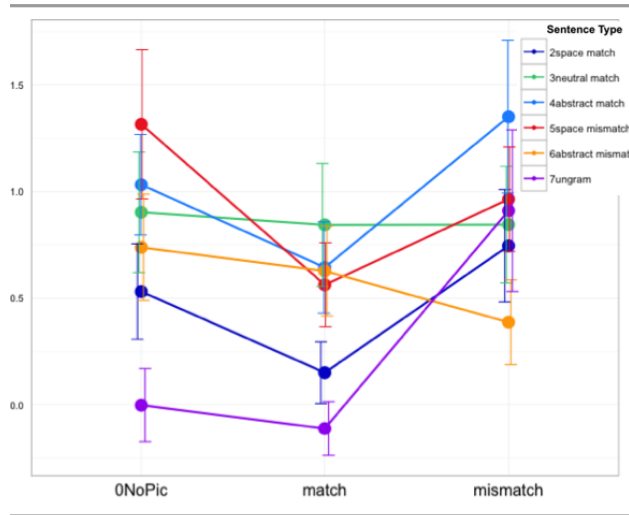


Figure A.11: Rating-time data by spatial picture type by each experimental sentence type

Whether the picture matched the object mentioned in the sentence significantly affected reading times, but not rating times or rating scores: reading times ( $p=.01367$ ). Rating score ( $p=.2041$ ) and rating time ( $p=.2014$ ). Conditions included: Non-spatial matches/control, spatial match, spatial mismatch, and space neutral. Conditions excluded: Idiom match, idiom mismatch and ungrammatical.

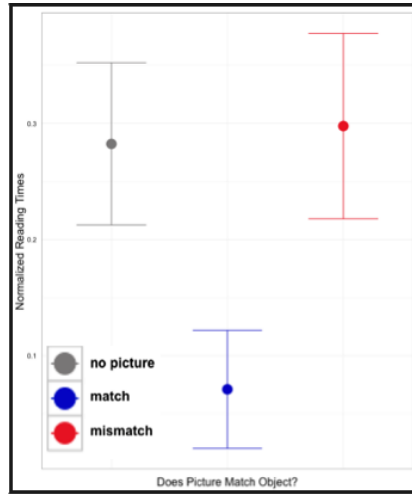


Figure A.12: Reading-time data by picture type averaged across all experimental sentences

The model that best fit the reading-time data for the concrete items was that which included both sentence type and picture type factors (whether the picture matched the object) as explanatory factors. This model was significantly better than when sentence type or picture type were used as explanatory factors alone. An ANOVA was used to compare fits for the model that combined these explanatory factors and a model that only included sentence type as an explanatory factory. This comparison was significant,  $p = 0.013$ .

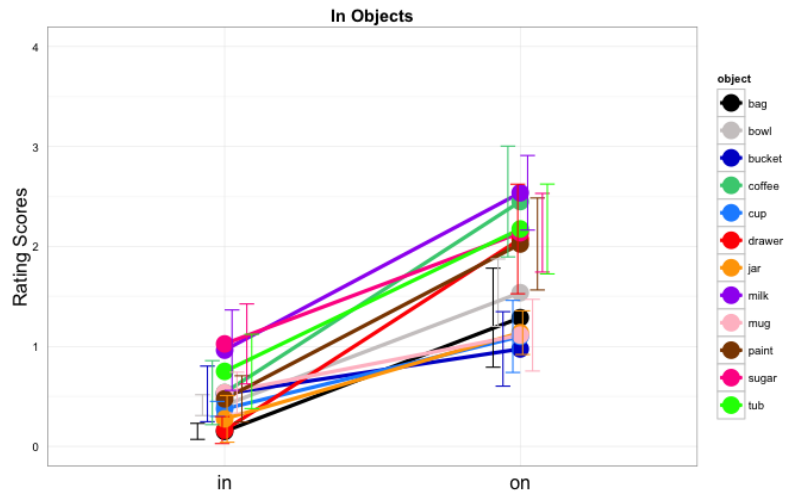
Again, the model that included the interaction between picture type and sentence type was significantly better at explaining reading time variance compared to each variable on its own, but was not significantly better than the model that included both sentence type and picture type as explanatory variables.

### A.3.3 Sentence Ratings For *In* Objects and *On* Objects

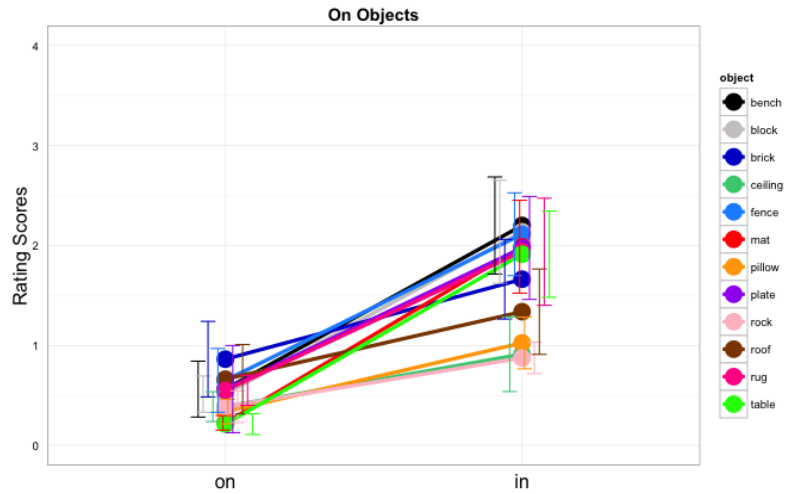
Participants distinguished between the spatial match and spatial mismatch sentences, so that a sentence containing the phrase *on the table* was rated as less surprising as one containing the phrase *in the table*, no matter what picture preceded it.

This result is in accordance with the findings from Feist and Gentner (1998, 2001) and Coventry and Prat-Sala (2001), who found that varying the features of a reference object in a prepositional phrase with *in* and *on* will yield variations in ratings of appropriateness for that phrase. Because Feist and Gentner used only five objects in their experiments, and because Coventry and Prat-Sala were interested in objects that hold liquids and those that do not, it was necessary to include additional objects in this study that had not previously been tested. Twenty-four objects were used in all: Twelve were labeled "*in* objects" and twelve were labeled "*on* objects". These objects were selected based on their spatial features which comply with those described by Herskovitz (1986).

The individual mean rating scores for the sentences containing these objects generally conform to a categorical distinction between *in* and *on* objects, so that most *in* objects were rated as less surprising after *in* and more surprising after *on* and vice versa for *on* objects. See Figure A.13 for rating patterns after *in* and *on* for all twenty-four concrete space reference nouns.



(a) In object ratings



(b) On object ratings

Figure A.13: Ratings for *in* and *on* objects used in concrete space match and mismatch sentences

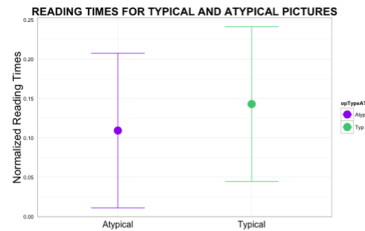
Two nouns, the *in* object "bucket" and the *on* object "roof", did not achieve sta-

tistically different mean rating scores after *in* versus *on*. However, both nouns did earn a lower mean rating scores when they were presented after the matching preposition (i.e., *in* for "bucket" and *on* for "roof").

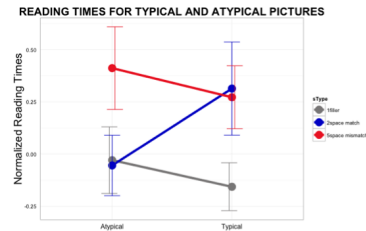
#### **A.3.4 Reading and rating times for concrete sentences across picture types**

For the concrete match, mismatch and non-spatial match sentences, objects were sometimes shown in a typical way and sometimes in an atypical way. For instance, a bowl was sometimes shown with its open side up (typical) and sometimes with its open side down (atypical). It was predicted that typical photographic depictions of objects would be better primes for nouns than atypical depictions would, and that this would be measurable by reading-time effects. However, there was not a significant effect of typicality on reading times across nor within these sentence types.





(a) Reading times for sentences after atypical (left, purple) and typical (right, green) depictions of objects, averaged across concrete match, mismatch and conjunction match sentences.

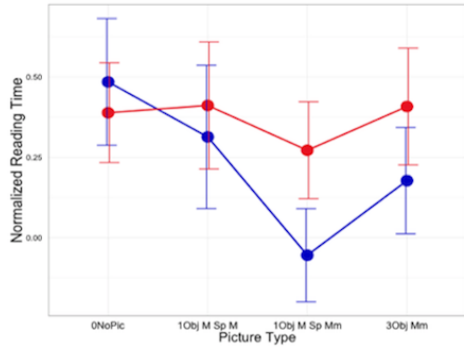


(b) Reading times for sentences after atypical (left) and typical (right) depictions of objects, for concrete match (blue), mismatch (red) and conjunction match (gray) sentences.

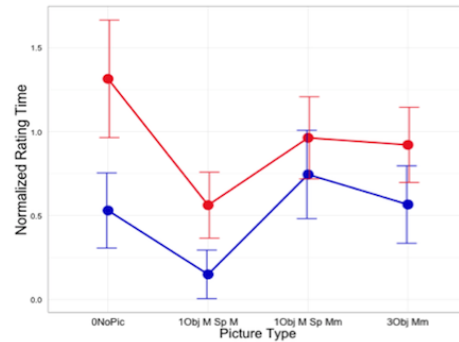
Figure A.14: Reading times for sentences after atypical and typical photographic depictions of objects.

When comparing reading times across picture types for the spatial match and mismatch condition, a pattern emerges, where the fastest mean reading times occurred after participants had seen objects that matched the object in the sentence, but when the object's spatial configuration did *not* match the preposition in the sentence. This pattern is not significant for the spatial mismatch condition, but it just reaches significance for the spatial match condition. The pattern of rating times across picture conditions is also remarkably similar for the spatial match and mismatch sentences, but shows the opposite pattern from the reading-time data. For both of these sentence types, rating times are shortest when the picture shown before the sentence is of a matching object in a matching spatial configuration. Again this pattern is significant for the concrete match sentences (e.g., *there is the flep in the bowl*), but not for the concrete mismatch sentences (e.g., *there is the*

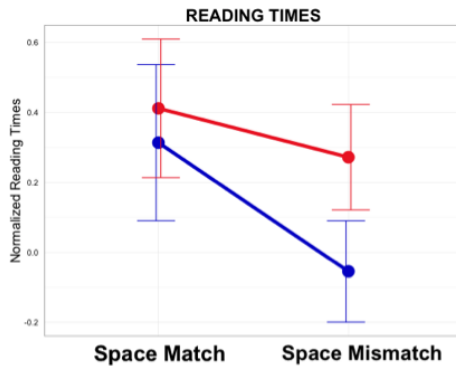
*flep on the bowl).*



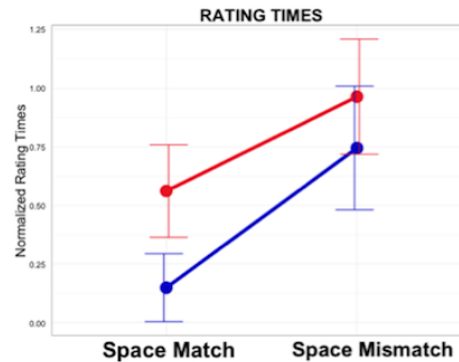
(a) Reading times to spatial match (blue) and spatial mismatch (red) sentences by picture type: no picture, spatially matching object, spatially mismatched object, object mismatch (respectively)



(b) Rating times to spatial match (blue) and spatial mismatch (red) sentences by picture type: no picture, spatially matching object, spatially mismatched object, object mismatch (respectively)



(c) Reading times to spatial match (blue) and spatial mismatch (red) sentences after spatially matched and spatially mismatched pictures



(d) Rating times to spatial match (blue) and spatial mismatch (red) sentences after spatially matched and spatially mismatched pictures

Figure A.15: Reading and rating times after different picture types for spatial match and spatial mismatch sentences.

If quicker reading times indicate better priming between visual and linguistic stimuli, the results from this study suggest that a picture of an upside-down bowl is better at priming *in* the bowl than a right-side-up bowl is. And, strangely, the op-

posite is true for *on* the bowl, where a picture of a right-side-up bowl is better at priming on the bowl than an upside down bowl is (though this difference is not significant). This is a very strange pattern, since it is likely that a canonical picture of a bowl is a better prime for bowl than a non-canonical picture is, and it is unclear that this priming effect should differ between sentences that contain *in* and those that contain *on*.

If, however, reading times are interpreted as a measure of both priming and *integration* between visual and linguistic information, these results are explicable. A picture of a bowl probably primes the word "bowl", which in turn speeds up reading times for sentences that mention a bowl (see Figure A.12). But, when the spatial configuration of the picture of the bowl matches the spatial configuration described in the sentence, participants attempt to integrate the linguistic information with the picture. This integration process results in relatively long *reading* times for sentences when they are shown after a spatially matching picture (see Figure A.15a and A.15c), but relatively short *rating* times, since participants have more thoroughly considered the sentence's meaning by the time they proceed to the rating stage (see Figure A.15b and A.15d). And, vice versa, when the spatial configuration of the bowl does not match the spatial configuration described in the sentence, integration between visual and linguistic information is not attempted, which results in the fastest reading times and slower rating times.

Interestingly, this integration process (if it does in fact take place) does not seem to occur consciously, since it does not significantly affect the ratings themselves.

Sentences' levels of "surprise" are not significantly lower in the cases when pictures match the spatial information of the sentence, compared to spatial mismatch pictures. However, since participants were not instructed to base their ratings on the connection between each sentence and its preceding visual stimulus, it is possible that participants were conscious of a visual-to-linguistic integration process, but did not allow that to affect their ratings for each sentence.

## **A.4 Conclusions**

Taken together, the rating score, reading and rating time data from the pilot study reveal a multi-faceted interaction between the mechanisms involved in processing, interpreting and evaluating spatial language, object knowledge and visual information. As shown in Chapter 4, the results from the ERP study also shows this interaction.

## Appendix B

### Supplements to methods

	Phrase Type	Located Noun	Prep/ Conj	Reference Noun	Phrase
	Practice	bef	and	doorbell	the bef and the doorbell
	Practice	pleck	by	doorbell	the pleck by the doorbell
	Practice	bloop	near	bridge	the bloop near the bridge
	Practice	floom	under	bridge	the floom under the bridge
	Practice	frop	with	bridge	the frop with the bridge
	Practice	mep	with	necklace	the mep with the necklace
1	Abstract Match	thrim	in	afternoon	the thrim in the afternoon
2	Abstract Match	flep	in	dark	the flep in the dark
3	Abstract Match	smard	in	evening	the smard in the evening
4	Abstract Match	pag	in	future	the pag in the future
5	Abstract Match	hace	in	know	the hace in the know
6	Abstract Match	wid	in	majority	the wid in the majority
7	Abstract Match	smag	in	mix	the smag in the mix
8	Abstract Match	flep	in	moment	the flep in the moment
9	Abstract Match	wid	in	morning	the wid in the morning
10	Abstract Match	barm	in	movie	the barm in the movie
11	Abstract Match	foom	in	red	the foom in the red

12	Abstract Match	deg	in	wrong	the deg in the wrong
13	Abstract Match	foom	on	double	the foom on the double
14	Abstract Match	nish	on	hour	the nish on the hour
15	Abstract Match	pag	on	internet	the pag on the internet
16	Abstract Match	fent	on	make	the fent on the make
17	Abstract Match	flep	on	mark	the flep on the mark
18	Abstract Match	hace	on	mend	the hace on the mend
19	Abstract Match	crund	on	rise	the crund on the rise
20	Abstract Match	barm	on	run	the barm on the run
21	Abstract Match	wid	on	take	the wid on the take
22	Abstract Match	thrim	on	uptake	the thrim on the uptake
23	Abstract Match	pleck	on	verge	the pleck on the verge
24	Abstract Match	jare	on	whole	the jare on the whole
25	Abstract Mismatch	scur	in	double	the scur in the double
26	Abstract Mismatch	hace	in	hour	the hace in the hour
27	Abstract Mismatch	barm	in	internet	the barm in the internet
28	Abstract Mismatch	nish	in	make	the nish in the make
29	Abstract Mismatch	toose	in	mark	the toose in the mark
30	Abstract Mismatch	mun	in	mend	the mun in the mend
31	Abstract Mismatch	frid	in	rise	the frid in the rise
32	Abstract Mismatch	sletch	in	run	the sletch in the run
33	Abstract Mismatch	hace	in	take	the hace in the take
34	Abstract Mismatch	scur	in	uptake	the scur in the uptake
35	Abstract Mismatch	mun	in	verge	the mun in the verge
36	Abstract Mismatch	hace	in	whole	the hace in the whole
37	Abstract Mismatch	flep	on	afternoon	the flep on the afternoon
38	Abstract Mismatch	deek	on	dark	the deek on the dark
39	Abstract Mismatch	frip	on	evening	the frip on the evening
40	Abstract Mismatch	troil	on	future	the troil on the future
41	Abstract Mismatch	thrim	on	know	the thrim on the know
42	Abstract Mismatch	stook	on	majority	the stook on the majority
43	Abstract Mismatch	pleck	on	mix	the pleck on the mix
44	Abstract Mismatch	hace	on	moment	the hace on the moment
45	Abstract Mismatch	flep	on	morning	the flep on the morning
46	Abstract Mismatch	toose	on	movie	the toose on the movie
47	Abstract Mismatch	frid	on	red	the frid on the red
48	Abstract Mismatch	toose	on	wrong	the toose on the wrong
49	Conjunction Control	smard	and	apple	the smard and the apple

50	Conjunction Control	fent	and	banana	the fent and the banana
51	Conjunction Control	runk	and	brush	the runk and the brush
52	Conjunction Control	bock	and	button	the bock and the button
53	Conjunction Control	jare	and	candle	the jare and the candle
54	Conjunction Control	smard	and	candy	the smard and the candy
55	Conjunction Control	crund	and	carrot	the crund and the carrot
56	Conjunction Control	troil	and	chalk	the troil and the chalk
57	Conjunction Control	frid	and	cloud	the frid and the cloud
58	Conjunction Control	sletch	and	curtain	the sletch and the curtain
59	Conjunction Control	smag	and	flag	the smag and the flag
60	Conjunction Control	cron	and	guitar	the cron and the guitar
61	Conjunction Control	scur	and	hammer	the scur and the hammer
62	Conjunction Control	plark	and	knife	the plark and the knife
63	Conjunction Control	crund	and	lamp	the crund and the lamp
64	Conjunction Control	nish	and	match	the nish and the match
65	Conjunction Control	toose	and	pen	the toose and the pen
66	Conjunction Control	mun	and	pencil	the mun and the pencil
67	Conjunction Control	pag	and	penny	the pag and the penny
68	Conjunction Control	flep	and	pin	the flep and the pin
69	Conjunction Control	crund	and	plant	the crund and the plant
70	Conjunction Control	clorp	and	rope	the clorp and the rope
71	Conjunction Control	semp	and	string	the semp and the string
72	Conjunction Control	plark	and	sun	the plark and the sun
73	Conjunction Match	toose	and	bag	the toose and the bag
74	Conjunction Match	semp	and	bench	the semp and the bench
75	Conjunction Match	pag	and	block	the pag and the block
76	Conjunction Match	clorp	and	bowl	the clorp and the bowl
77	Conjunction Match	runk	and	brick	the runk and the brick
78	Conjunction Match	gan	and	bucket	the gan and the bucket
79	Conjunction Match	clorp	and	ceiling	the clorp and the ceiling
80	Conjunction Match	sletch	and	coffee	the sletch and the coffee
81	Conjunction Match	gan	and	cup	the gan and the cup
82	Conjunction Match	smard	and	drawer	the smard and the drawer
83	Conjunction Match	smag	and	fence	the smag and the fence
84	Conjunction Match	barm	and	jar	the barm and the jar
85	Conjunction Match	crund	and	mat	the crund and the mat
86	Conjunction Match	wid	and	milk	the wid and the milk
87	Conjunction Match	gan	and	mug	the gan and the mug

88	Conjunction Match	deg	and	paint	the deg and the paint
89	Conjunction Match	pleck	and	pillow	the pleck and the pillow
90	Conjunction Match	runk	and	plate	the runk and the plate
91	Conjunction Match	smag	and	rock	the smag and the rock
92	Conjunction Match	flep	and	roof	the flep and the roof
93	Conjunction Match	pag	and	rug	the pag and the rug
94	Conjunction Match	fent	and	sugar	the fent and the sugar
95	Conjunction Match	deek	and	table	the deek and the table
96	Conjunction Match	troil	and	tub	the troil and the tub
97	Space Match	frip	in	bag	the frip in the bag
98	Space Match	mun	in	bowl	the mun in the bowl
99	Space Match	crund	in	bucket	the crund in the bucket
100	Space Match	thrim	in	coffee	the thrim in the coffee
101	Space Match	crund	in	cup	the crund in the cup
102	Space Match	clorp	in	drawer	the clorp in the drawer
103	Space Match	deek	in	jar	the deek in the jar
104	Space Match	frip	in	milk	the frip in the milk
105	Space Match	clorp	in	mug	the clorp in the mug
106	Space Match	fent	in	paint	the fent in the paint
107	Space Match	toose	in	sugar	the toose in the sugar
108	Space Match	stiss	in	tub	the stiss in the tub
109	Space Match	cron	on	bench	the cron on the bench
110	Space Match	thrim	on	block	the thrim on the block
111	Space Match	plark	on	brick	the plark on the brick
112	Space Match	mun	on	ceiling	the mun on the ceiling
113	Space Match	bock	on	fence	the bock on the fence
114	Space Match	cron	on	mat	the cron on the mat
115	Space Match	bock	on	pillow	the bock on the pillow
116	Space Match	plark	on	plate	the plark on the plate
117	Space Match	scur	on	rock	the scur on the rock
118	Space Match	drung	on	roof	the drung on the roof
119	Space Match	thrim	on	rug	the thrim on the rug
120	Space Match	foom	on	table	the foom on the table
121	Space Mismatch	stook	in	bench	the stook in the bench
122	Space Mismatch	plark	in	block	the plark in the block
123	Space Mismatch	stiss	in	brick	the stiss in the brick
124	Space Mismatch	nish	in	ceiling	the nish in the ceiling
125	Space Mismatch	deek	in	fence	the deek in the fence



126	Space Mismatch	gan	in	mat	the gan in the mat
127	Space Mismatch	troil	in	pillow	the troil in the pillow
128	Space Mismatch	stiss	in	plate	the stiss in the plate
129	Space Mismatch	runk	in	rock	the runk in the rock
130	Space Mismatch	foom	in	roof	the foom in the roof
131	Space Mismatch	foom	in	rug	the foom in the rug
132	Space Mismatch	pleck	in	table	the pleck in the table
133	Space Mismatch	deg	on	bag	the deg on the bag
134	Space Mismatch	cron	on	bowl	the cron on the bowl
135	Space Mismatch	pleck	on	bucket	the pleck on the bucket
136	Space Mismatch	smag	on	coffee	the smag on the coffee
137	Space Mismatch	stook	on	cup	the stook on the cup
138	Space Mismatch	runk	on	drawer	the runk on the drawer
139	Space Mismatch	smard	on	jar	the smard on the jar
140	Space Mismatch	semp	on	milk	the semp on the milk
141	Space Mismatch	troil	on	mug	the troil on the mug
142	Space Mismatch	jare	on	paint	the jare on the paint
143	Space Mismatch	fent	on	sugar	the fent on the sugar
144	Space Mismatch	mun	on	tub	the mun on the tub

Table B.1: 144 phrases used for ERP experiment (Plus six practice items)

		PHRASE TYPE				
		Concrete Conjunction	Concrete Spatial Match	Concrete Spatial Mismatch	Abstract Spatial Match	Abstract Spatial Mismatch
PICTURE TYPE	No Picture	1	5	9	13	17
	" <i>in</i> version" of object	2	-	-	-	-
	" <i>on</i> version" of object	3	-	-	-	-
	Spatially matched object	-	6	10	14	18
	Spatially mismatched object	-	7	11	15	19
	Unrelated object	4	8	12	16	20


Table B.2: Twenty epochs used for analysis of reference nouns. Nouns were grouped by phrase type and picture type. For spatial phrases, nouns that followed *in* and *on* were averaged together.

		PHRASE TYPE	
		Preposition	Conjunction
PICTURE TYPE	No Picture	1	5
	" <i>in</i> version" of object	-	6
	" <i>on</i> version" of object	-	7
	Spatially matched object	2	-
	Spatially mismatched object	3	-
	Unrelated object	4	8

Table B.3: Eight different preposition and conjunction epochs used for analysis. Phrases were grouped by phrase type and picture type. For prepositions, *in* and *on* were averaged together.

# Appendix C

## Consent forms



Ph.D. Program in Speech and Hearing Sciences  
The Graduate Center, City University of New York  
365 5th Avenue, 12th Floor  
New York, NY 10016-4309  
Tel: 212-646-6000 Fax: 212-646-6007

**CUNY UI - Institutional Review Board**  
Approval Date: December 30, 2013  
Expiration Date: December 29, 2014  
Coordinator Initials: CP

**CONSENT FORM TO PARTICIPATE IN A LANGUAGE EXPERIMENT**

The purpose of this form is to help you decide whether you want to volunteer for a research study. Read carefully and ask the investigator about anything that you do not understand.

**STUDY TITLE: A place for PLACE and a path for PATH in the brain: An ERP study of responses to different types of prepositional phrases**

PERSONS IN CHARGE: Emily Zane, MA, Linguistics, The Graduate Center, CUNY.  
STUDY LOCATION: City University of New York, The Graduate Center

**GENERAL INFORMATION**

- This study examines how English speakers finish incomplete sentences and how English speakers predict the ending of sentences. The study will examine how English speakers make about how a sentence will end after hearing the beginning of that sentence and b) about what types of sentences sound good or bad to English speakers.
- Approximately 30 adults will participate in this study.
- This study will consist of one visit to the Developmental Neurolinguistic Lab. The entire visit will take approximately 40 minutes.

**PROCEDURE**

- You will either be asked to rate sentences as good, bad, or weird. This testing will take approximately 20 minutes plus any additional break time necessary to help you feel comfortable.
- Breaks will be provided often during testing, and you may stop at any time.

**BENEFITS OF VOLUNTEERING**

- This research will not directly benefit you, but it will help us to understand the way adults comprehend and process language.
- Before participating in the experiment, you will receive the results of a free hearing test.

**RISKS OF VOLUNTEERING**

- You may become tired or bored during the testing session.

**CONFIDENTIALITY OF YOUR RECORDS**

- Your records, including testing forms and audiotapes, will be kept in a locked file cabinet to protect your privacy.
- Results of this study may be published, but will not include your name or other information that could be used to identify you.
- If results from this study are published, you will receive a copy if you provide your contact information.

**VOLUNTEERING**

- You may stop at any time.
- You may stop participating in this study at any time.

**CONTACT INFORMATION**

- If you have questions about this research, contact Emily Zane, Principle Investigator at 212-817-8833, [ezane@gc.cuny.edu](mailto:ezane@gc.cuny.edu) or Valerie Shafer, Faculty Advisor at 212-817-8805, [vshafer@gc.cuny.edu](mailto:vshafer@gc.cuny.edu)
- To learn about your rights as a research volunteer, contact Kay Powell, IRB Administrator, (212) 817-7525 or [Apowell@gc.cuny.edu](mailto:Apowell@gc.cuny.edu).

**CONSENT** – By signing this form, I agree that:

- I have read this form, or I have had it read to me in my native language.
- I have had the opportunity to ask questions about this research, and I have received satisfactory answers.

**INVESTIGATOR STATEMENT**

- I have carefully explained the nature of this study to the participant signing this form. To the best of my knowledge, the person signing this form understands the risks and benefits involved with participating in this study.

Printed Name of participant \_\_\_\_\_

Signature \_\_\_\_\_

Date \_\_\_\_\_

Printed name of investigator \_\_\_\_\_

Signature \_\_\_\_\_

Date \_\_\_\_\_

**CUNY UI - Institutional Review Board**  
Approval Date: December 30, 2013  
Expiration Date: December 29, 2014  
Coordinator Initials: CP

Figure C.1: Consent form given to participants who participated in behavioral pilot experiment

**CUNY UI - Institutional Review Board**  
**Approval Date: December 30, 2013**  
**Expiration Date: December 29, 2014**  
**Coordinator Initials: CP**

The Graduate Center  
 The City University of New York  
 350 Fifth Avenue  
 New York, NY 10018  
 Tel: 212-646-6000 Fax: 212-646-6001

**CONSENT FORM TO PARTICIPATE IN A LANGUAGE EXPERIMENT**

The purpose of this form is to help you decide whether you want to volunteer for a research study. Read carefully and ask the investigator about anything that you do not understand.

**STUDY TITLE: A place for PLACE and a path for PATH in the brain: An ERP study of responses to different types of prepositional phrases**

**PERSONS IN CHARGE:** Emily Zane, MA, Linguistics and Valerie Shafer, Professor, Ph.D., Program in Speech-Language-Hearing Sciences, The Graduate Center, CUNY.

**STUDY LOCATION:** City University of New York, The Graduate Center

**GENERAL INFORMATION**

- This research examines the brain responses of adults when listening to different types of English sentences. The results of this experiment will shed light on the way that people understand and process different types of English sentences.
- Approximately 30 adults will participate in this study.
- This study will consist of one visit to the Developmental Neurolinguistic Lab. The visit will take approximately 1.5 hours.

**PROCEDURE**

- You will take part in a study that examines brain activity while listening to sentences and looking at pictures of geometric shapes. A net of electrodes will be placed on your head. The electrodes make contact with the hair/scalp through damp sponges. The electrode net is hooked up to a device that records your brainwaves while listening to the language. This testing will take approximately 40 minutes plus any additional break time necessary to help you feel comfortable.
- Breaks will be provided often during testing, and you may stop at any time.

**BENEFITS OF VOLUNTEERING**

- This research will not directly benefit you, but it will help us to understand the way adults comprehend and process sentences.
- Before participating in the EEG experiment, you will receive a free hearing test.

**RISKS OF VOLUNTEERING**

- You may become tired or bored during the testing session.
- You may feel discomfort due to application or wearing of the electrode net.

**COMPENSATION**

- You will be compensated \$10 per hour for your time participating in this study.

**CONFIDENTIALITY OF YOUR RECORDS**

- Your records, including testing forms, will be kept in a locked file cabinet to protect your privacy.
- Results of this study may be published, but will not include your name or other information that could be used to identify you.
- If results from this study are published, you will receive a copy if you provide your contact information.

**VOLUNTEERING**

- You are not being asked to volunteer if you want to, and for no other reason.
- You may stop participating in this study at any time.

**CONTACT INFORMATION**

- If you have questions about this research, contact Emily Zane, Principle Investigator at 212-817-8833, [ezane@gc.cuny.edu](mailto:ezane@gc.cuny.edu) or Valerie Shafer, Professor at 212-817-8805, [vshafer@gc.cuny.edu](mailto:vshafer@gc.cuny.edu)

**CONSENT** – By signing this form, I agree that:

- I understand that I am being asked to participate in a research study in my native language.
- I have had the opportunity to ask questions about this research, and I have received satisfactory answers.
- I understand that I am being asked to volunteer to participate in research.
- I understand the risks and benefits of this study.
- I understand that I will be videotaped during the study.
- I freely give my consent to participate in this research.
- I will receive a signed copy of this form.

Printed Name of participant \_\_\_\_\_ Signature \_\_\_\_\_ Date \_\_\_\_\_

**INVESTIGATOR STATEMENT**

- I have carefully explained the nature of this study to the participant signing this form. To the best of my knowledge, the person signing this form understands the risks and benefits involved with participating in this study.

Printed name of investigator \_\_\_\_\_ Signature \_\_\_\_\_ Date \_\_\_\_\_

CUNY UI - Institutional Review Board

Approval Date: December 30, 2013  
 Expiration Date: December 29, 2014  
 Coordinator Initials: CP

Figure C.2: Consent form given to participants who participated in ERP experiment

# Appendix D

## Supplementary Figures

### D.1 Graphs of comparisons not included in analysis

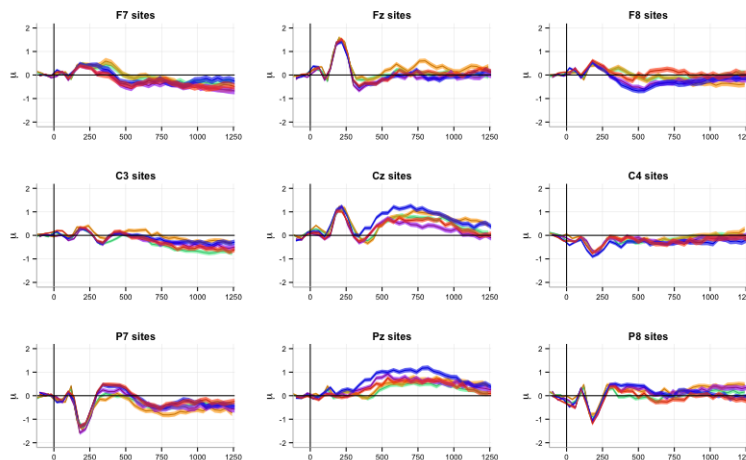


Figure D.1: Responses to all five reference noun types (abstract match, abstract mismatch, spatial match, spatial mismatch, and conjunction match) for 9 regions selected by identifying overlapping electrodes determined by the spatial PCA performed on concrete and abstract reference nouns. Abstract match depicted in green, abstract mismatch in orange, conjunction match in purple, spatial match in blue, spatial mismatch in red.

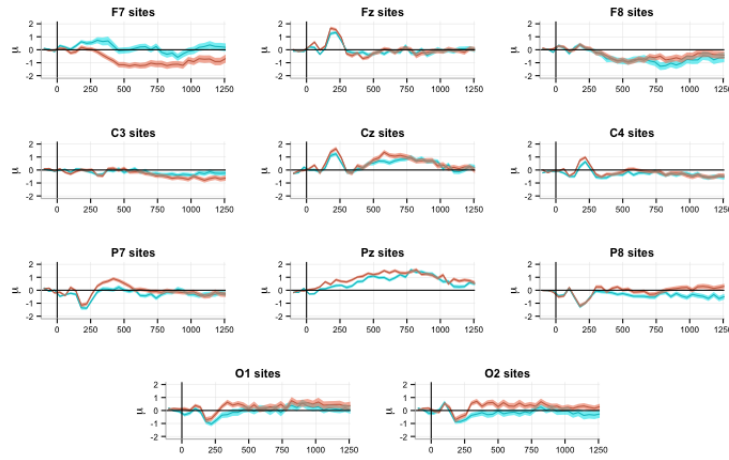


Figure D.2: Responses to spatial match nouns after atypical versions of reference objects were presented in the preceding photograph (red) or typical versions of reference objects were presented in the preceding photograph (turquoise).

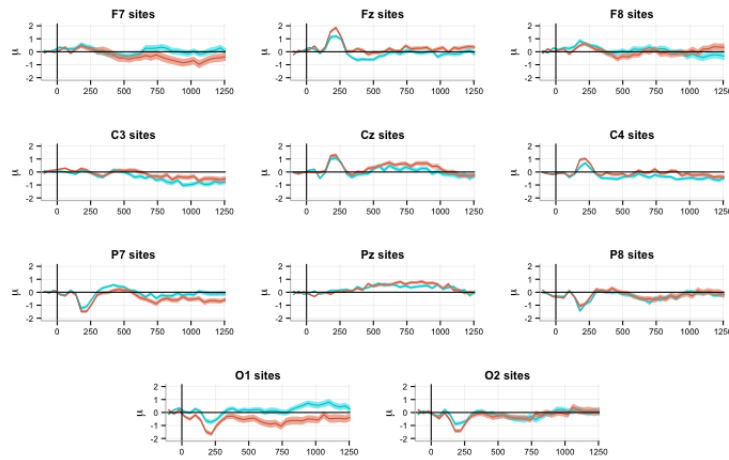


Figure D.3: Responses to spatial mismatch nouns after atypical versions of reference objects were presented in the preceding photograph (red) or typical versions of reference objects were presented in the preceding photograph (turquoise).

## D.2 Graphs of concrete noun comparisons

### D.2.1 Full epoch

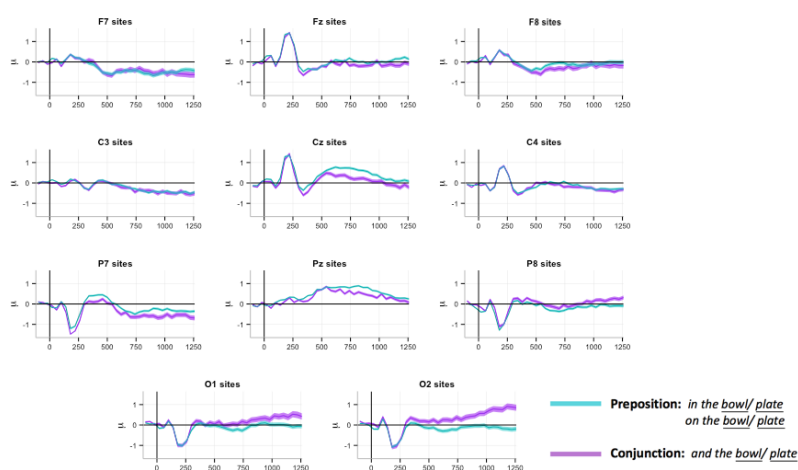


Figure D.4: Responses to nouns at eleven spatial regions chosen from rotated components for five time windows for the two different phrase types: Conjunction and preposition (averaged across spatial match and spatial mismatch). Turquoise lines represent averages across preposition phrases and purple is conjunction phrase (see legend at bottom right). Averaged across all four picture conditions for all phrases.



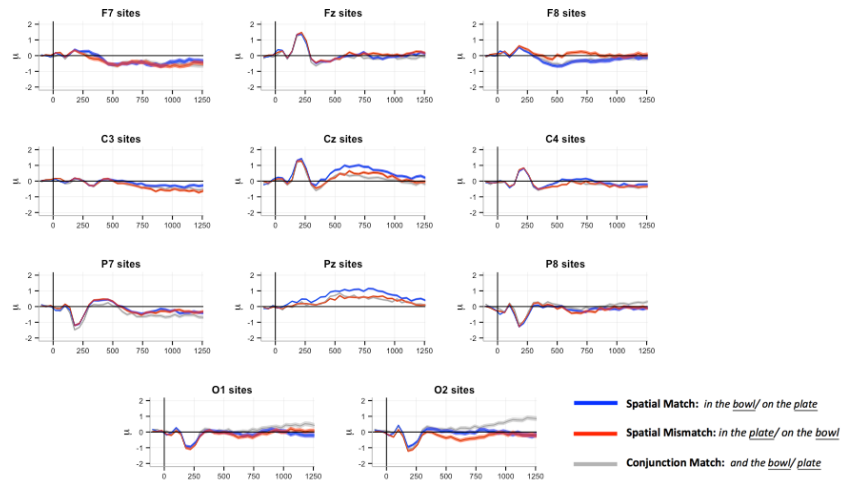
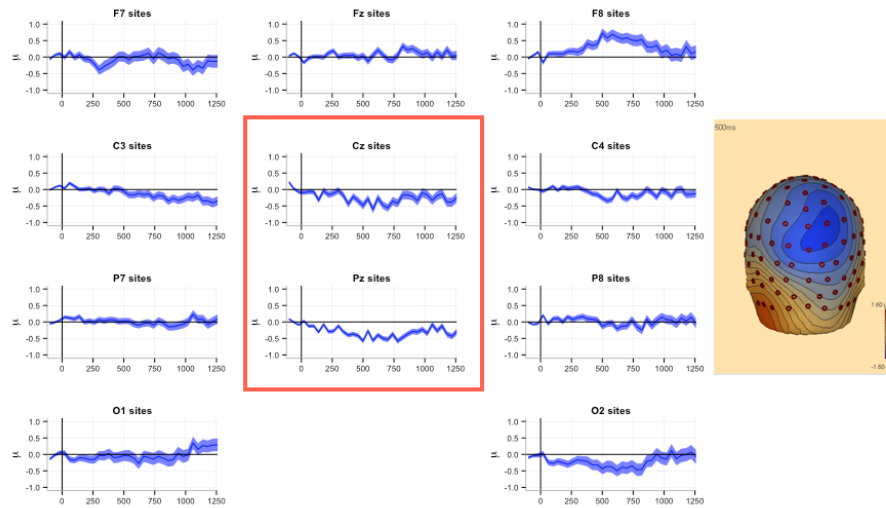


Figure D.5: Responses to different reference noun types at eleven spatial regions chosen from rotated components for five time windows. Gray is conjunction match, blue is spatial match, red is spatial mismatch (see legend at bottom right).



*in the plate/on the bowl* **MINUS** *on the plate/in the bowl*

Figure D.6: Subtracted responses between spatial mismatch nouns and spatial match nouns (spatial mismatch- spatial match) at all regions selected from spatial PCA, with regions showing N400 responses outlined in pink. Right: Topomap of this subtraction at 500ms post-noun onset.

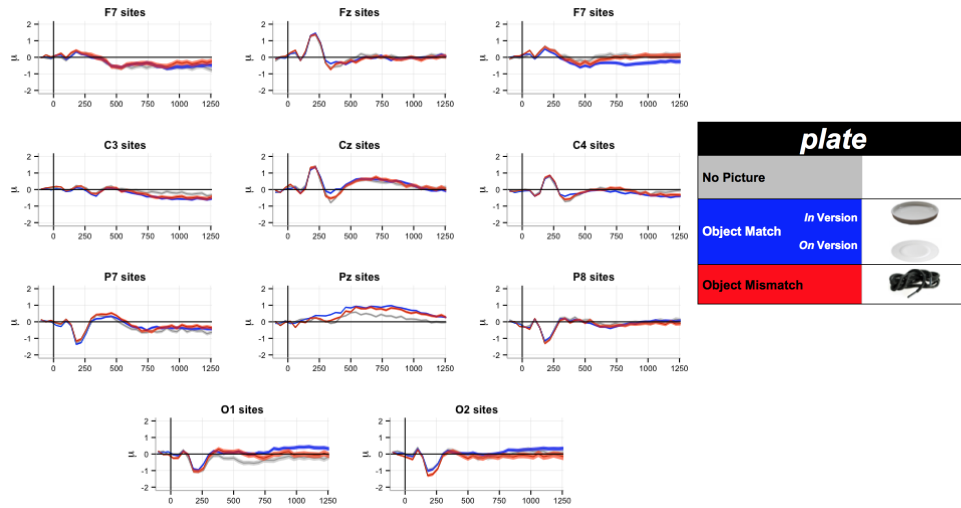


Figure D.7: Responses at eleven spatial regions chosen from rotated components for five time windows. Waveforms represent responses averaged across all nouns (conjunction match, spatial match and spatial mismatch) after no picture was shown (gray), after a matching object was shown (blue), and after a random, mismatching object was shown (red). See legend (right) for example pictures.

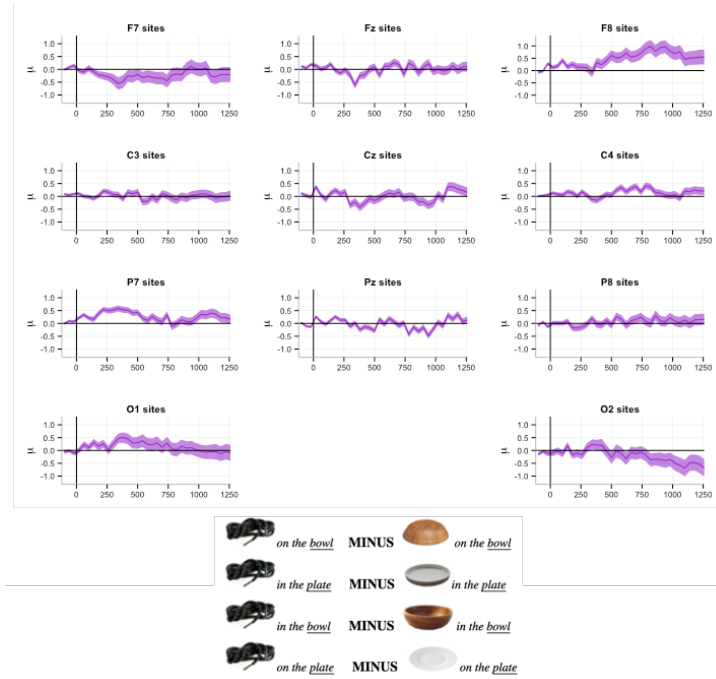


Figure D.8: Subtracted responses between nouns in spatial phrases after pictures of mismatched objects and nouns after pictures of matched (and spatially matching) objects. See legend at bottom for examples.

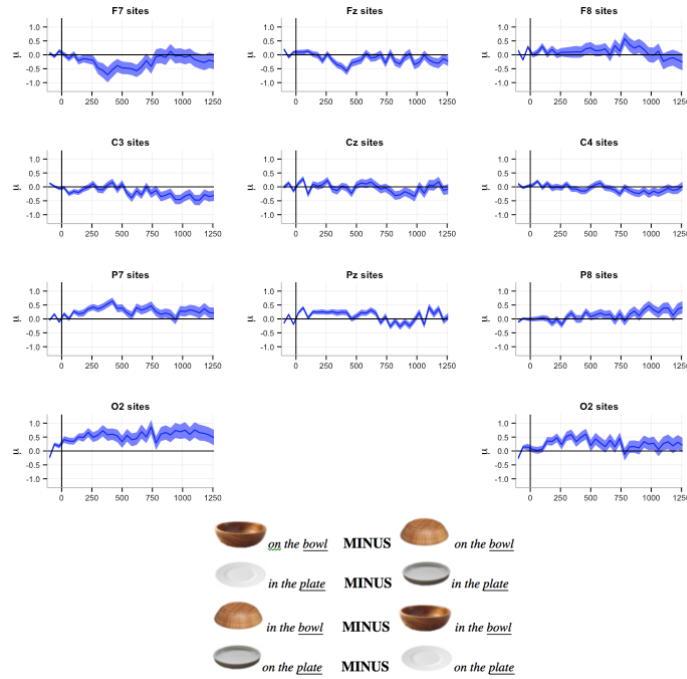
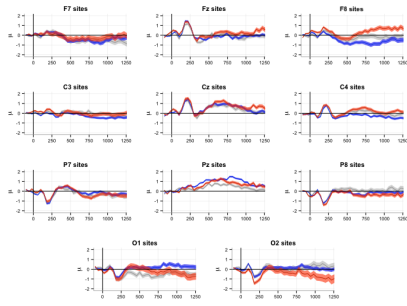
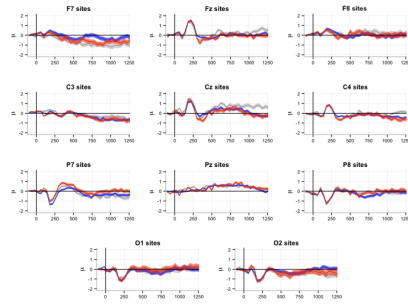


Figure D.9: Subtracted responses between nouns in spatial phrases after pictures of spatially mismatching objects and nouns after pictures of spatially matching objects. See legend at bottom for examples.

Spatial match nouns (e.g., "on the plate")



Spatial mismatch nouns (e.g., "in the plate")



Conjunction match nouns (e.g., "and the plate")

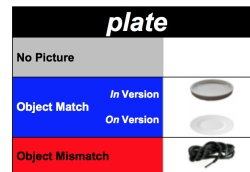
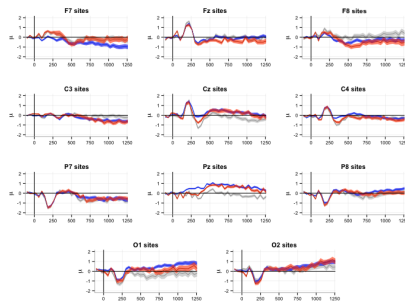


Figure D.10: Responses to nouns in spatial match, spatial mismatch and conjunction phrases after seeing no picture (gray), a picture of a matching object (blue), and a picture of a random object (red).

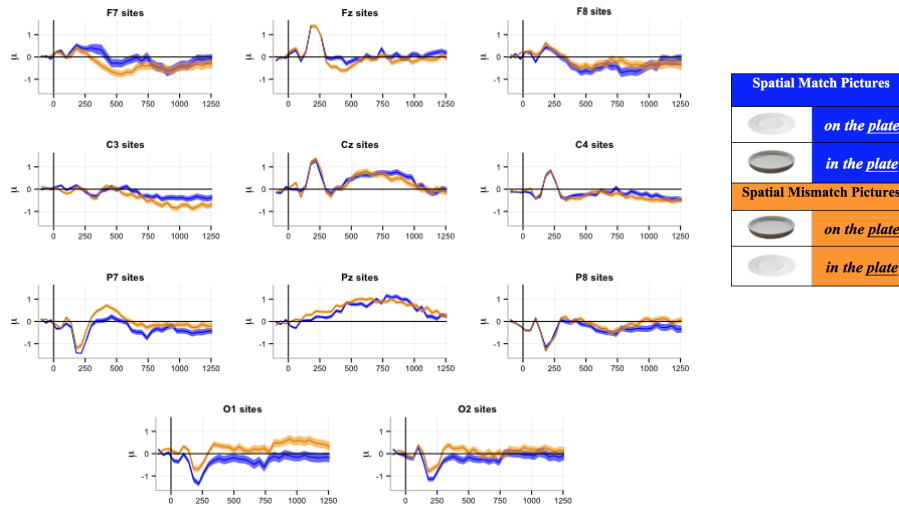


Figure D.11: Responses at eleven spatial regions chosen from rotated components for five time windows. For this figure, responses to concrete nouns in prepositional phrases are displayed for the two experimental picture conditions– when the spatial configuration of the picture matches the space of the preposition (e.g., a picture of a concave plate before "in the plate" or a picture of a flat plate before "on the plate") and when the spatial configuration of the picture does not match the space of the preposition (e.g., a picture of a concave plate before "on the plate" or a picture of a flat plate before "in the plate"). Dark blue waveforms are ERPs when the spatial configuration of the object matches the preposition, orange waveforms are when the spatial configuration of the object is mismatched for the preposition in the phrase. See the legend (right) for example pictures for phrases containing the noun *plate*

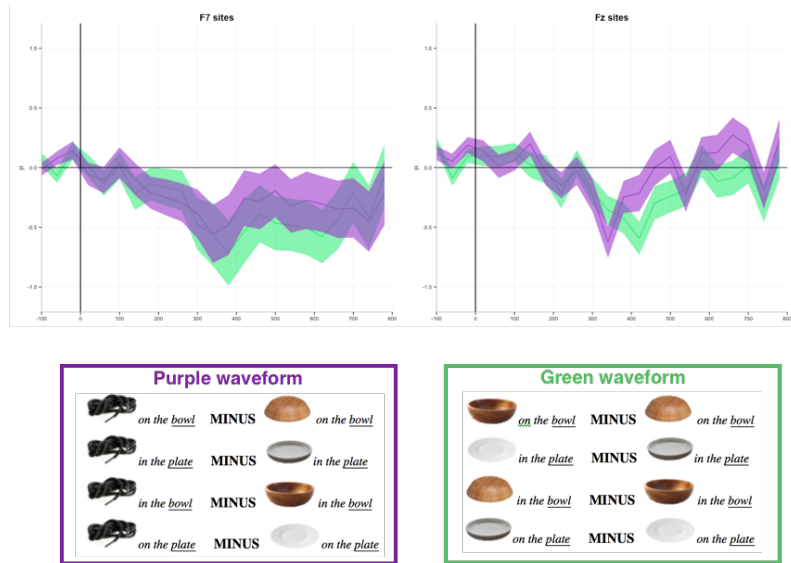


Figure D.12: Resulting waveforms when responses to nouns after spatially matching pictures are subtracted from responses to nouns after spatially mismatching pictures (leaving the difference) and when responses to nouns after pictures of matching objects in matching spatial configurations are subtracted from responses to nouns after pictures of random objects in left frontal and medial frontal regions. See legends at bottom for examples of picture-to-phrase pairings for each difference.



## D.2.2 Responses to concrete nouns in five time windows of interest

### D.2.2.1 First time window of analysis

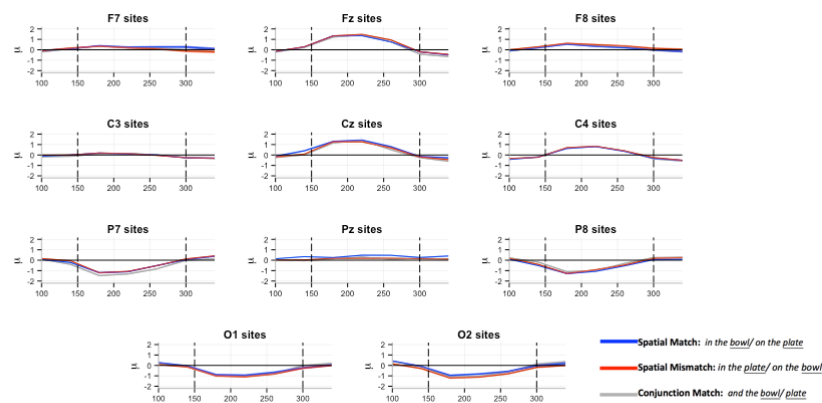


Figure D.13: Responses to different reference noun types at eleven spatial regions chosen from rotated components for the first time window. Gray is conjunction match, blue is spatial match, red is spatial mismatch (see legend at bottom right). Dotted lines represent beginning and end of first epoch of interest (150 to 300ms post-noun onset).

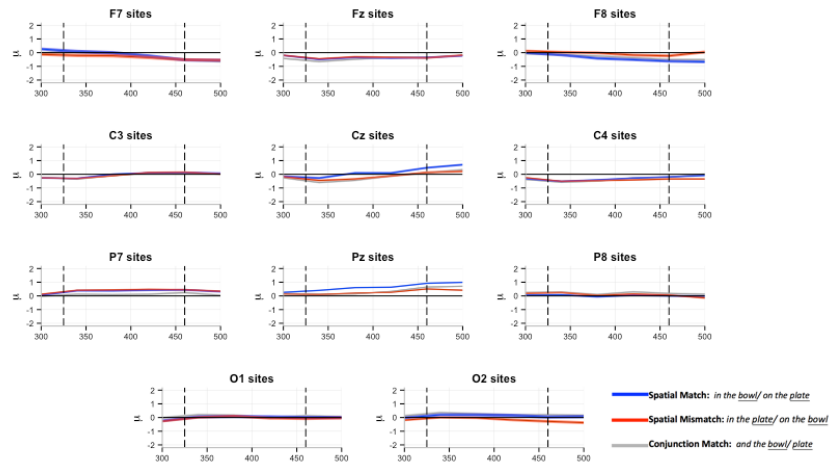


Figure D.14: Responses to different reference noun types at eleven spatial regions chosen from rotated components for the second time window. Gray is conjunction match, blue is spatial match, red is spatial mismatch (see legend at bottom right). Dotted lines represent beginning and end of first epoch of interest (340 to 460ms post-noun onset).

### D.2.2.2 Second time window of analysis

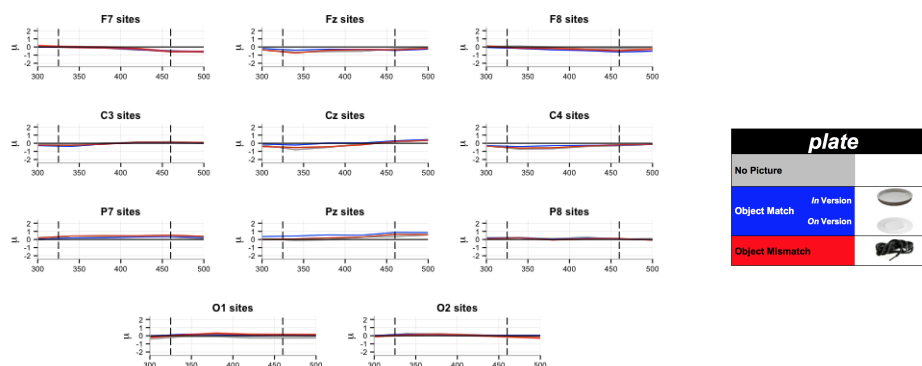


Figure D.15: Responses at eleven spatial regions chosen from rotated components for the second time window. Waveforms represent responses averaged across all nouns (conjunction match, spatial match and spatial mismatch) after no picture was shown (gray), after a matching object was shown (blue), and after a random, mismatching object was shown (red). See legend (right) for example pictures. Dotted lines represent beginning and end of second epoch of interest (340 to 460ms post-noun onset).

### D.2.2.3 Third time window of analysis

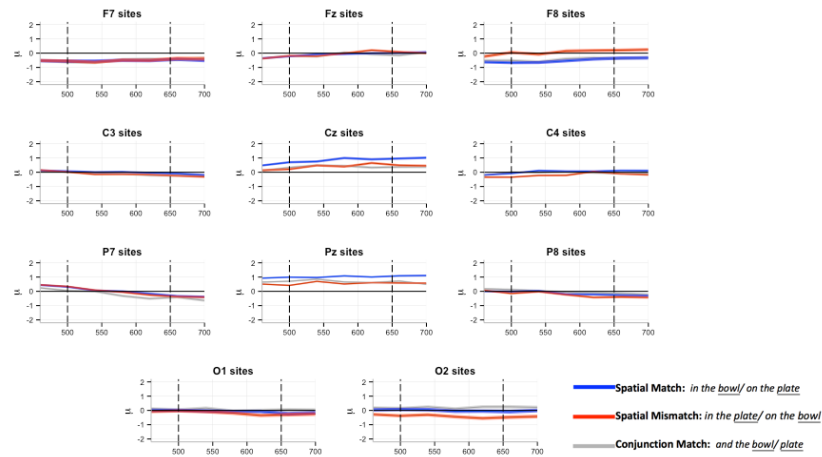


Figure D.16: Responses to different reference noun types at eleven spatial regions chosen from rotated components for third time window of interest post-noun onset. Gray is conjunction match, blue is spatial match, red is spatial mismatch (see legend at bottom right). Dotted lines represent beginning and end of third epoch of interest (500 to 650ms post-noun onset).

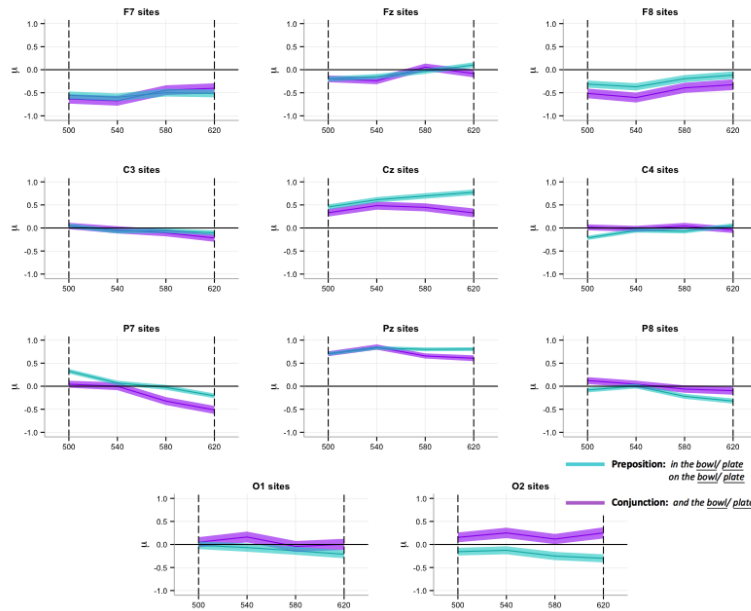


Figure D.17: Responses to nouns at eleven spatial regions chosen from rotated components for third time window of interest post-noun onset for two different phrase types: Conjunction and preposition (averaged across spatial match and spatial mismatch). Turquoise lines represent averages across preposition phrases and purple is conjunction phrase (see legend at bottom right). Averaged across all four picture conditions for all phrases. Dotted lines represent beginning and end of third epoch of interest (500 to 620ms post-noun onset).

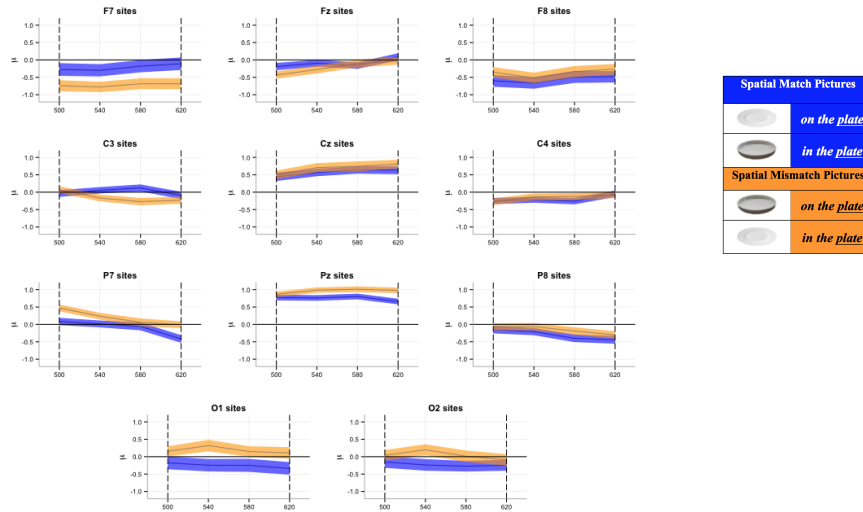


Figure D.18: Responses at eleven spatial regions chosen from rotated components for the third time window. For this figure, responses to concrete nouns in prepositional phrases are displayed for the two experimental picture conditions– when the spatial configuration of the picture matches the space of the preposition (e.g., a picture of a concave plate before "in the plate" or a picture of a flat plate before "on the plate") and when the spatial configuration of the picture does not match the space of the preposition (e.g., a picture of a concave plate before "on the plate" or a picture of a flat plate before "in the plate"). Dark blue waveforms are ERPs when the spatial configuration of the object matches the preposition, orange waveforms are when the spatial configuration of the object is mismatched for the preposition in the phrase. Dotted lines represent beginning and end of third epoch of interest (500 to 620ms post-noun onset). See the legend (right) for example pictures for phrases containing the noun *plate*.

#### D.2.2.4 Fourth time window of analysis

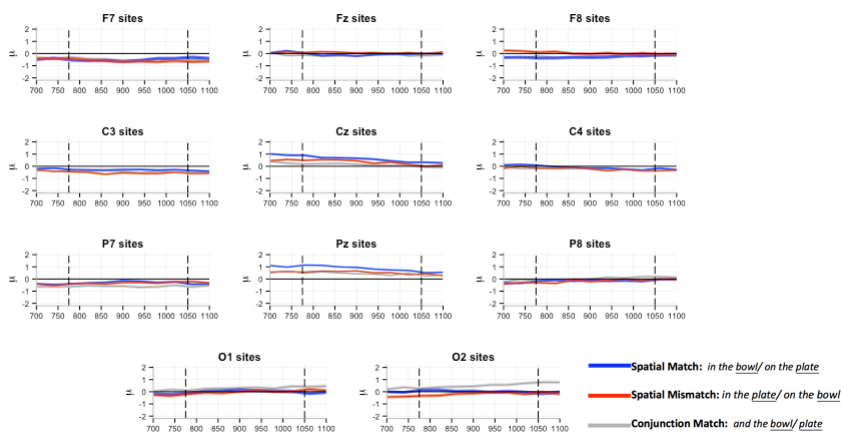


Figure D.19: Responses to different reference noun types at eleven spatial regions chosen from rotated components for fourth time window of interest post-noun onset. Gray is conjunction match, blue is spatial match, red is spatial mismatch (see legend at bottom right). Dotted lines represent beginning and end of fourth epoch of interest (780 to 1020ms post-noun onset).

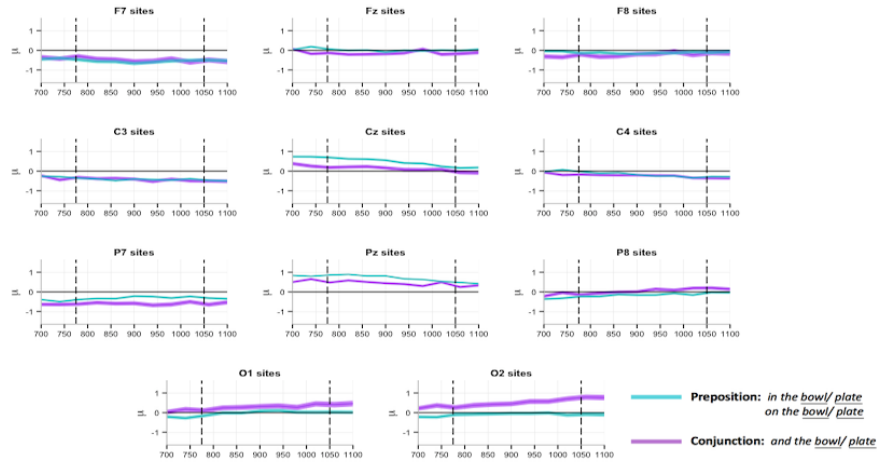


Figure D.20: Responses to nouns at eleven spatial regions chosen from rotated components for fourth time window of interest post-noun onset for two different phrase types: Conjunction and preposition (averaged across spatial match and spatial mismatch). Turquoise lines represent averages across preposition phrases and purple is conjunction phrase (see legend at bottom right). Averaged across all four picture conditions for all phrases. Dotted lines represent beginning and end of fourth epoch of interest (780 to 1020ms post-noun onset).



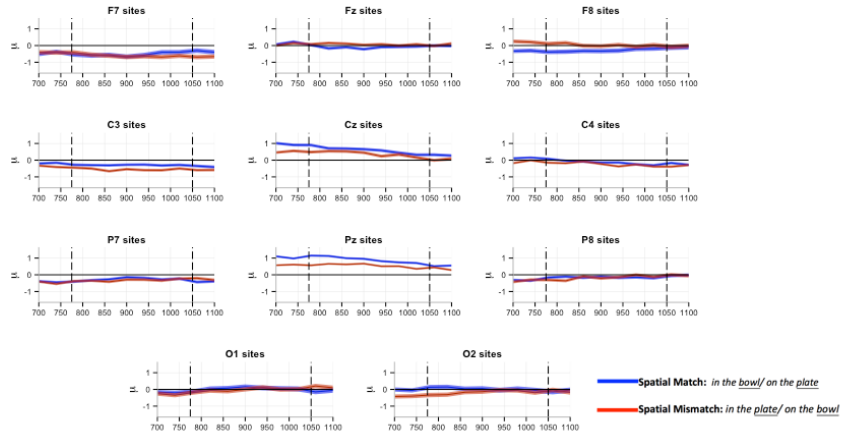


Figure D.21: Responses to experimental reference nouns at eleven spatial regions chosen from rotated components for last time window of interest post-noun onset. Blue is spatial match, red is spatial mismatch (see legend at bottom right). Dotted lines represent beginning and end of fourth epoch of interest (780 to 1020ms post-noun onset).

### D.2.2.5 Last time window of analysis

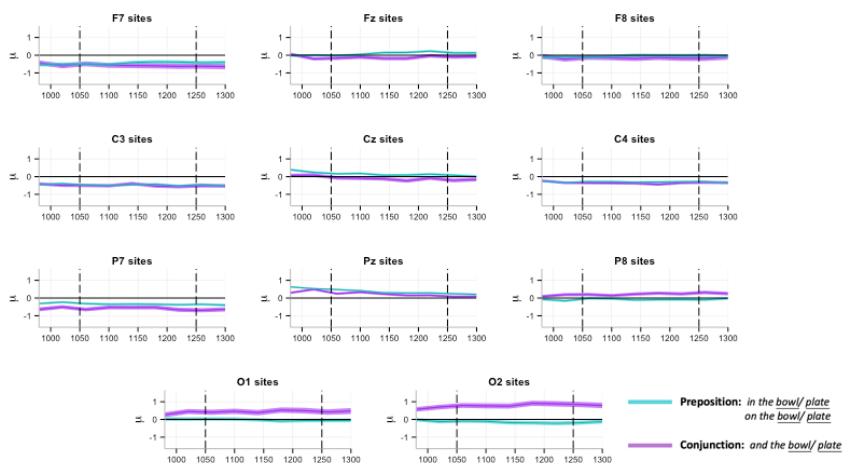


Figure D.22: Responses to nouns at eleven spatial regions chosen from rotated components for last time window of interest post-noun onset for two different phrase types: Conjunction and preposition (averaged across spatial match and spatial mismatch). Turquoise lines represent averages across preposition phrases and purple is conjunction phrase (see legend at bottom right). Averaged across all four picture conditions for all phrases. Dotted lines represent beginning and end of last epoch of interest (1060 to 1220ms post-noun onset).

### D.3 Graphs of abstract noun comparisons

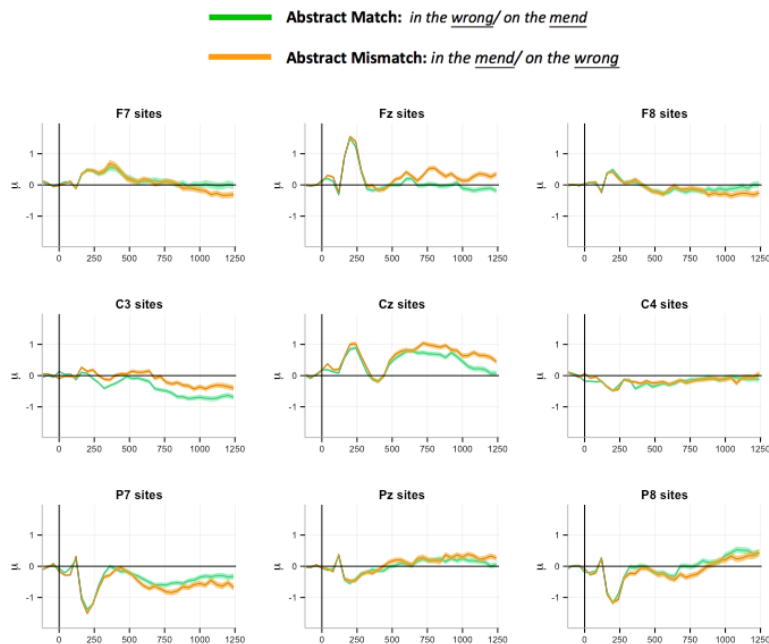


Figure D.23: Responses to abstract match (green) and abstract mismatch (orange) nouns.

## D.4 Responses to prepositions and conjunctions

### D.4.1 Full epoch

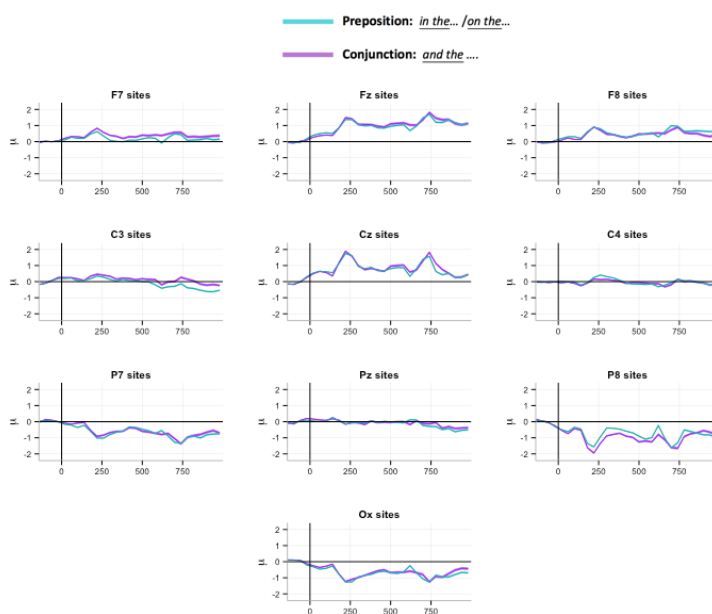


Figure D.24: Responses at ten spatial regions chosen from rotated components for five time windows for the two different phrase types: Conjunction and preposition. Spatial match and spatial mismatch are averaged together for the preposition phrases. Turquoise is Preposition Phrase and purple is Conjunction Phrase.

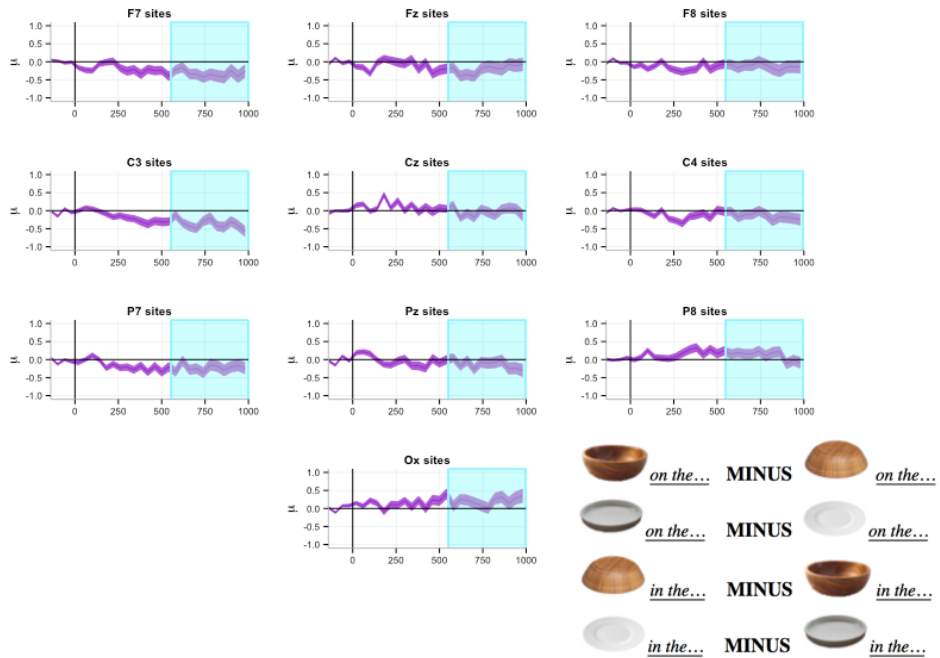


Figure D.25: Resulting waveforms when responses to prepositional phrases (e.g., *in/on the...*) after seeing spatially matching pictures (*in* version of objects before *in* phrases and *on* version of objects before *on* phrases) are subtracted from responses to phrases after seeing spatially mismatching pictures (*in* version of objects before *on* phrases and *on* version of objects before *in* phrases) at ten spatial regions chosen from rotated components. *In/on* phrases are averaged together. See legend. The time region of interest (from 550-1000 milliseconds post-preposition onset) is after the preposition is no longer displayed on the screen. This time region is highlighted in turquoise on each graph.

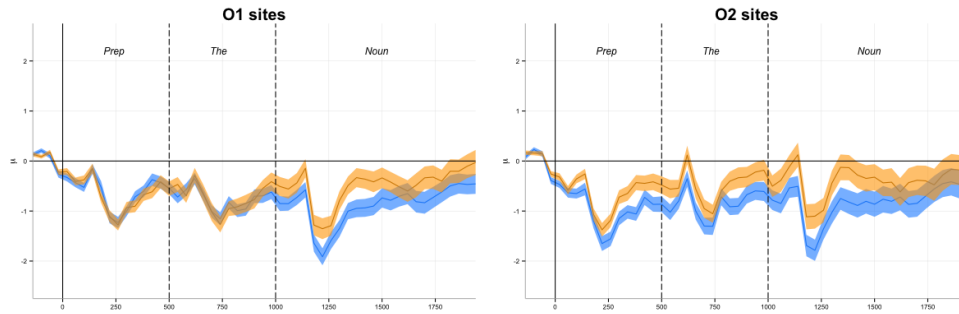
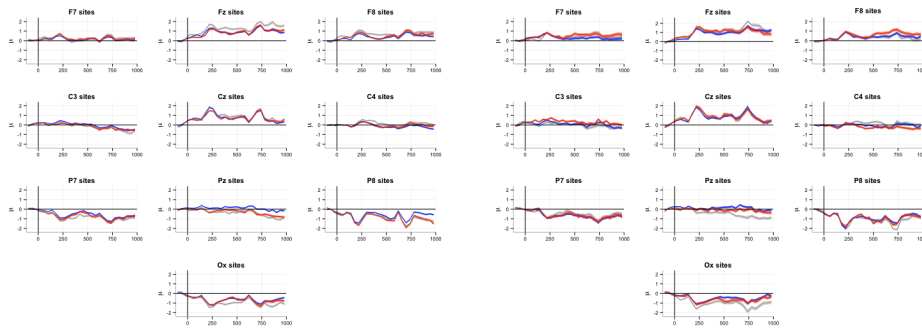


Figure D.26: Responses to prepositions *in* and *on* after spatially matching pictures (shown in blue) and after spatially mismatching pictures (shown in orange) at O1 and O2 sites.



(a) Responses to prepositions after no picture (gray), after a picture of an *in/on* object (blue), or after a random object whose spatial/functional properties do not match either *in* or *on* (red)

(b) Responses to conjunctions after no picture (gray), after a picture of an *in/on* object (blue), or after a random object whose spatial/functional properties do not match either *in* or *on* (red)

Figure D.27: Responses to prepositions (left) and conjunctions (right) after seeing pictures of no objects, pictures of *in/on* objects, and after seeing pictures of objects whose spatial/functional properties match neither *in* nor *on*.

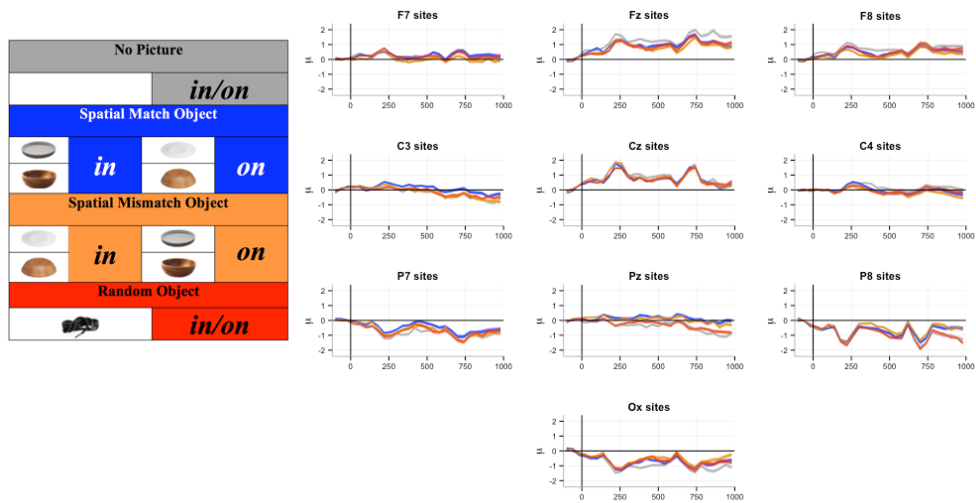
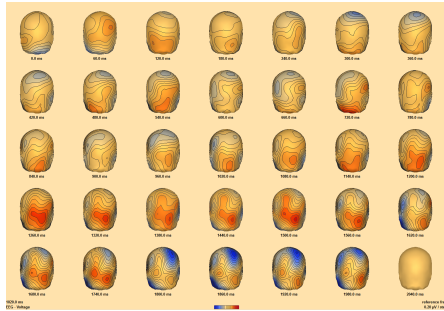
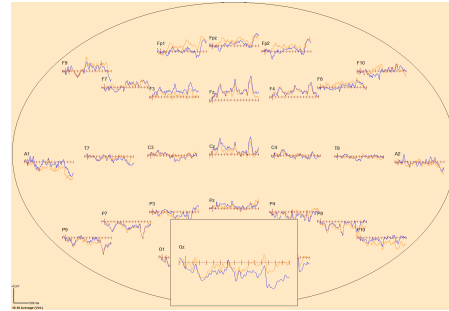


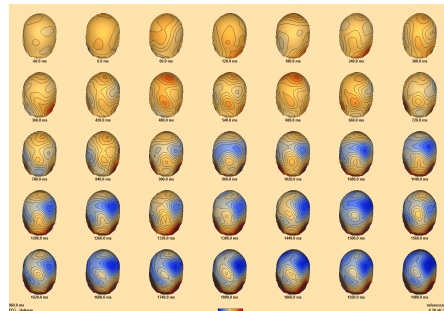
Figure D.28: Responses to prepositions after specific picture types (No Picture, Spatially Matching Picture, Spatially Mismatching Picture, and Random Object). noun types at ten spatial regions chosen from rotated components for five time windows. Gray is No Picture, blue is Spatially Matching, yellow is Spatially Mismatching and red is Random Object. See legend at left for example pictures for *in* and *on*.



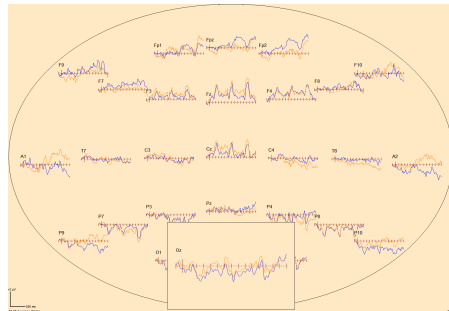
(a) Topoplots at the back of the head showing the result when responses to *on* after pictures of objects in *on* configurations are subtracted from responses to *on* after pictures of objects in *in* configurations.



(b) Responses to *on* after pictures of objects in *on* configurations- shown in blue- and after pictures of objects in *in* configurations- shown in orange



(c) Topoplots at the back of the head showing the result when responses to *in* after pictures of objects in *in* configurations are subtracted from responses to *in* after pictures of objects in *on* configurations.



(d) Responses to *in* after pictures of objects in *in* configurations- shown in blue- and after pictures of objects in *on* configurations- shown in orange

Figure D.29: Topoplots at the back of the head showing occipital positivities to prepositions *on* (left) and *in* (right) after spatially matched pictures as compared to responses after spatially mismatched pictures.



## Appendix E

### Comparisons excluded from main analysis

#### E.1 N400 effects to nouns based on the object shown in the picture

The effect of the type of object shown in the picture before the phrase had a marginally significant impact on responses between 340-460 milliseconds post-noun onset, reflecting relatively larger N400 responses to nouns after mismatching pictures (pictures of random objects) and after no pictures at all. The fact that this N400 effect was less significant than the N400 effects to nouns based on the preposition preceding the noun suggests that priming effects based on linguistic factors were stronger than priming effects based on visual (pictorial) factors, so that when a word was primed by the preceding preposition (as in the spatial match case), effects of picture type had a smaller impact on lexical retrieval. When the

word was not primed by the preceding phrase structure (as in the case of the spatial mismatch and conjunction match phrases), it seemed that picture type played a larger role in creating expectations.

This contrasts what was reported in Kuitunen (2007), who found that visual context outweighed sentential context in modulating the N400 response measured at the onset of the final word in a sentence. In his study, Kuitunen presented participants with pictures while playing sentences for them. The last word of each sentence was either anomalous or expected, e.g., *My friend usually commutes by donkey/ train*. The pictures they viewed were either congruous or incongruous with the sentences they heard (this was only evident at the last word of each sentence). ERPs were compared at the last word. Participants were asked to judge whether the sentence matched the picture. N400 responses were significantly larger when the sentences and pictures were incongruous. Anomalous words did not elicit larger N400 responses than expected words. Kuitunen takes these results as indicating that verbal and nonverbal meaning is processed in a unitary neural system (which is responsible for generating the N400 response).

Based on Kuitunen's interpretation of his findings, the largest N400 responses to reference nouns in the current study should have been those in which the reference noun did not match the preceding picture, regardless of the preceding preposition. However, the study reported here differs from Kuitunen's study in two crucial ways: First, participants were not asked to determine whether the phrase matched the previously-presented picture; second, the pictures were not shown simultane-

ous to the presentation of the phrase, but instead were shown beforehand. It is possible that Kuitunen's results were in part caused by the fact that participants focused on determining whether the final noun matched the picture, rather than processing the sentences in a normal way. Further, since in Kuitunen's study, the pictures remained on the screen while the participants listened to the sentence and since every sentence's final noun was responsible for determining whether the sentence matched that picture, it is possible that participants were simply waiting to see whether the final word's label matched a salient component in the visible context. Because the current study used pictures as primes and because the task requires that participants focus on the words in the phrase rather than on picture-to-sentence matching, it is possible that it provoked a less conscious interaction between picture-to-word, so that visual context did not completely override sentential context in the generation of N400 responses.

## **E.2 N400s to concrete versus abstract nouns**

The research questions for this study (and, therefore, the hypotheses) did not include comparisons between ERPs to abstract and concrete reference nouns. Therefore, comparisons between all five reference noun types (conjunction match, spatial match, spatial mismatch, abstract match and abstract mismatch) are not discussed in this chapter. However, post-hoc, repeated-measures ANOVAs, comparing all five reference nouns were conducted. Five time regions and 9 electrode regions used for these comparisons were determined by selecting overlapping time

windows and electrodes identified by the spatial/temporal PCAs performed for concrete and abstract reference noun segments. See Figure D.1 in D for responses to the five different reference noun types at all nine electrode regions.

These five ANOVAs (one for each of the time windows of interest) yielded significant effects of reference noun type in the second time window (340 and 500 milliseconds post-noun onset) and third time window (between 560 and 700 milliseconds post-noun onset). Between 340 and 500 milliseconds post-noun onset, there was a significant interaction between reference noun type (conjunction match, abstract match, abstract mismatch, spatial match, spatial mismatch) and anteriority,  $F_{(8,216)} = 4.16$ ,  $p < 0.005$ ,  $\epsilon > 0.45$ , and a significant interaction between reference noun type and hemisphere,  $F_{(8,216)} = 2.19$ ,  $p < 0.05$ ,  $\epsilon > 0.80$ . In the following time window, between 560 and 700 milliseconds post-noun onset, there was a significant three-way interaction between reference noun type, anteriority, and hemisphere,  $F_{(16,432)} = 1.77$ ,  $p < 0.05$ ,  $\epsilon > 0.80$ .

These effects reflect a pattern where responses to the two abstract reference noun types (abstract match and mismatch) were different from responses to the three concrete reference noun types (spatial match, spatial mismatch, conjunction match). The N400 response to nouns peaks later and in more posterior regions (Pz as compared to Cz) for abstract nouns relative to concrete nouns. The N400 response was followed by a negativity for all five noun types in left and medial frontal regions (F7 and Fz), but this negativity was delayed and relatively smaller for abstract nouns. See Figure E.1 for responses to all five reference noun types at F7.

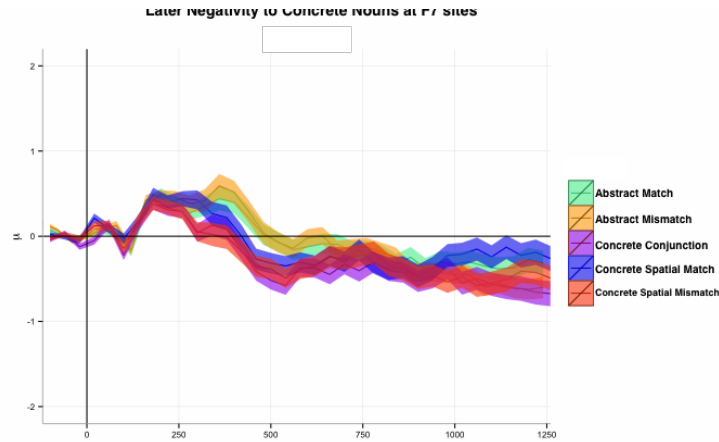


Figure E.1: Responses at F7 for all five reference noun types.

N400 latency delays to abstract words and the relatively large amplitudes to abstract phrases could merely reflect orthographic differences between the concrete and abstract nouns. Words with more characters take longer to retrieve from the lexicon, and show correspondingly delayed/larger N400 responses (Osterhout et al. 1997). The words used as abstract nouns were longer (had more characters) on average than words used in the concrete phrases, though this difference is not significant,  $p < 0.13$  for a 2-tailed t-test comparison.

On the other hand, according to Brysbaert et al. (2014) SUBTLEX measures, which provides word-frequency scores based on film subtitles, the nouns used in the abstract category were marginally significantly *more frequent* than the nouns in the concrete category,  $p < 0.08$  for a 2-tailed t-test comparison, which theoretically should decrease the N400 latency for the abstract nouns (Osterhout et al. 1997).

Interestingly, there was a large difference between the size of the N400 between the two match conditions, concrete spatial match (e.g., *in the bowl*) and abstract spatial match (e.g., *in the wrong*), where abstract match nouns yielded much larger N400 responses than concrete spatial match nouns did. See Figure E.2. This is a surprising result, since both nouns are semantically appropriate for the phrase in which they are presented, and should theoretically be primed by the preceding preposition.

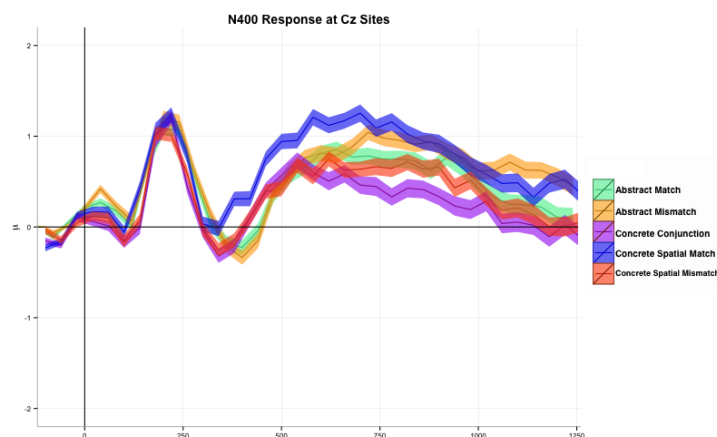


Figure E.2: Responses at Cz for all five reference noun types.

A likely contribution to N400 differences between abstract and concrete nouns might have been caused by frequency differences within the experiment itself. During the experiment, concrete nouns were used more frequently, since they were included in both concrete, spatial (prepositional) phrases and in concrete conjunction phrases. This meant that concrete nouns were repeated 33% more frequently than abstract nouns were throughout the experiment, so that concrete nouns may

have been primed more effectively than abstract nouns by this repetition (i.e., by "identity" priming) (e.g., Petten et al. (1991)).

The sustained, delayed relative negativity to concrete nouns as compared to abstract nouns (in frontal sites) was similar to what was reported in West and Holcomb (2000), where concrete nouns yielded ongoing relative negativities as compared to abstract nouns. In their study, they had participants perform three sentence-verification tasks, where verification depended on: 1) The imageability of the target noun (e.g., *It is easy to create a mental image of **shoes/bravery***); 2) The semantics of the target noun (e.g., *It is common for people to have an **elephant/aptitude***); 3) The surface (orthographic) features of the target noun (e.g., *The letter 'x' appears in the word **aluminum/dexterity***). In the first two paradigms, concrete nouns yielded significantly larger (more negative) N400 responses compared to abstract nouns, and concrete nouns elicited a sustained negativity (especially in anterior regions) relative to responses to abstract nouns. In the surface task, the same differences occurred, but were much smaller. They posit that the late, sustained anterior negativity (the "N700" or "frontal N400") to the concrete nouns indexes the use of mental imagery during processing. In the current study, participants were not ever asked to directly focus on features of the reference nouns (not even orthographic ones), so if this late negativity reveals processes involved in mental imagery formation/maintenance, then it shows that mental images are constructed for concrete nouns during typical language processing (during reading). It is interesting that West and Holcomb (2000) reported very small differences between this late anterior negativity to concrete versus abstract nouns in their surface task,

which, like the current study's task, did not encourage participants to focus on the meaning of the object or the visual form of its referent. However, in this study, nouns acted as referent objects in prepositional phrases; this may have spurred the production of mental images even during passive processing.

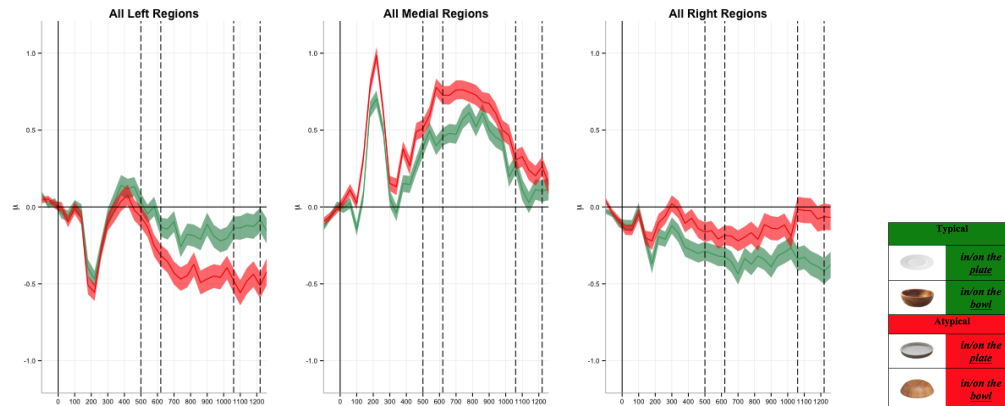
### **E.3 Typicality of picture**

In the pilot behavioral study, described in Appendix A, the typicality of an object's depiction did not significantly influence reading times across sentences. However, ERP measures have excellent temporal resolution, and can therefore reveal differences that are undetectable in behavioral paradigms. It was predicted the N400 response to reference nouns would be affected by the typicality of an object's depiction in visual primes, where more typical visual representations of a reference object (e.g., a flat plate) would prime each reference noun (e.g., "plate") more effectively than atypical pictures of objects (e.g., a concave plate) would. This finding would suggest either that the representation of the word "plate" is associated with particular conceptual, visuo-spatial features, or, that upon seeing a flat plate, the label "plate" is activated to a greater degree than the level of activation induced by a concave plate. This latter possibility could result from Plate 2 being a weaker representation of *plate* or because Plate 2 activates multiple labels -"dish", "bowl", "tray", etc.- which create competition, making the retrieval of "plate" more difficult.



A post-hoc set of repeated-measures ANOVAs explored the effects of object typicality on ERP responses to concrete nouns in prepositional phrases. These ANOVAs averaged across the same time windows (140-300ms, 340-460ms, 500-620ms, 780-1020ms, and 1060-1220ms) used for the other analyses of responses to concrete nouns and averaged across the same electrode sites for the 11 regions of interest: F7, Fz, F8, C3, Cz, C4, P7, Pz, P8, O1 and O2. Dependent factors were averaged voltage across these time windows in these sites. Independent factors were reference noun type (spatial match, spatial mismatch), picture type (typical, atypical), hemisphere (left, medial, right) and anteriority (frontal, central, posterior).

The interaction between hemisphere and typicality of reference object had a significant impact on voltage during the third (500-620ms) and last (1060-1220ms) epochs post-noun onset,  $F_{(2,54)} = 3.64$ ,  $p < 0.05$ ,  $\epsilon > 0.75$  and  $F_{(2,54)} = 4.32$ ,  $p < 0.05$ ,  $\epsilon > 0.95$ , respectively. These effects reflect a pattern whereby responses to nouns after pictures of atypical versions of the reference object were more negative in left regions, and were more positive in medial and right regions, see E.3.



(a) Responses to concrete nouns in spatial phrases (spatial match and spatial mismatch) after the presentation of typical pictures of reference objects (green) and atypical pictures of reference objects (red). Responses are averaged by hemisphere- left, medial, right. Time windows within which the interaction of hemisphere and typicality of picture were significant (500-620ms post-noun onset and 1060-1220ms post-noun onset) are indicated with dotted lines.

Figure E.3: Subtraction of responses to nouns after spatially matching pictures from responses to nouns after spatially mismatching pictures in left, central and right regions. Legend at right.

As is evident from responses in medial regions in Figure E.3, N400 responses were not larger after the presentation of atypical pictures of objects, but instead seemed to be larger after the presentation of *typical* pictures of objects (but not significantly so, since the main effect of typicality (or the interaction between typicality and hemisphere and/or anteriority) was not significant for the N400 time window (340-460ms post-noun onset).

During the N400 time window, the four-way interaction between reference noun type (spatial match versus spatial mismatch), typicality of the version of the ob-

ject presented in the photograph (typical versus atypical), hemisphere (left, right, medial) and anteriority (frontal, central, posterior) had a significant impact on voltage,  $F_{(4,108)} = 2.99$ ,  $p < 0.05$ ,  $\epsilon > 0.70$ . This result reflects overall, varying responses to spatial match and spatial mismatch phrases depending on whether the preceding picture was a typical version or atypical version of an object. For neither spatial match nor spatial mismatch nouns was there an N400 effect to nouns after the presentation of an atypical picture of an object. For example, see responses at Cz for Spatial match and mismatch nouns after the presentation of typical vs. atypical pictures in Figure E.4 (the Cz region was chosen since this region showed largest N400 effects to words and pictures for other comparisons in this study).

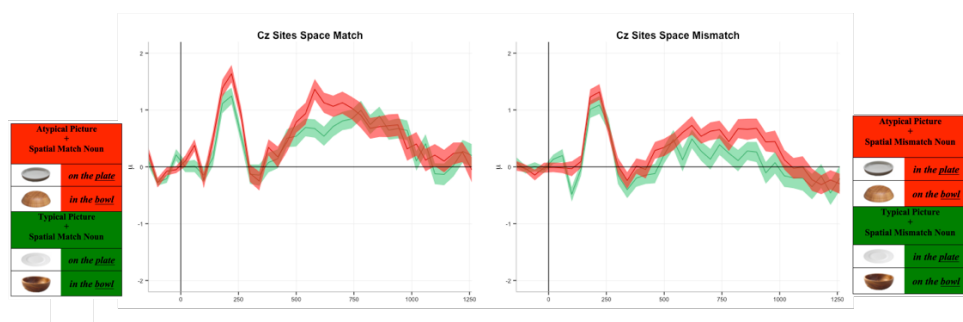


Figure E.4: Responses to concrete nouns in spatial match (left) and spatial mismatch (right) phrases after the presentation of typical pictures of reference objects (green) and atypical pictures of reference objects (red) in Cz sites.

In fact, for spatial mismatch nouns, a slightly larger N400 response was elicited to reference nouns after the presentation of *typical* configurations of objects. This is an odd result; however, since for spatial mismatch nouns, typical pictures were

also ones for which the spatial configuration of the object did not match the preposition in the phrase, it is probable that the spatial configuration of the object contributed more to the negativity observed in medial central sites (also observable in frontal central sites, see Figure D.3 in Appendix D). In other words, for spatial mismatch nouns, the typicality of an object's depiction and the spatial configuration of an object's depiction were confounding variables, so that every atypical picture was a match for spatial mismatch phrases and vice versa, every typical picture of an object was a mismatch for these phrases. More simply, to do this analysis, pictures that were labeled as "spatially mismatching" for the spatial mismatch phrases were now labeled as "typical" pictures of the objects and vice versa for the "spatially matching" pictures. The opposite was true for spatial match nouns, where every mismatch for the phrase was labeled "atypical" and every match was "typical". This meant that the influence of spatial factors (match vs. mismatch) and object typicality (typical vs. atypical) in pictures before spatial match nouns were re-categorizations of the same phenomena. If there had been a large N400 effect to nouns in spatial match phrases after the presentation of an atypical depiction of an object (There was not. See E.4 and D.2 in Appendix D), it would have been difficult to determine whether this response was influenced by the typicality (atypical) or the spatial configuration (mismatching) of the object in the photo.

Therefore, only consistent responses across spatial match and spatial mismatch nouns after typical versus atypical pictures were considered to be real effects of typicality. The only region in which such an effect was achieved was in left, frontal

regions (F7), for which a late, sustained negativity was elicited to reference nouns in both spatial match and mismatch phrases after the presentation of an atypical version/configuration of an object. This negativity was much larger for spatial match nouns (which may reflect contributions of the mismatch between the spatial features of the object shown before the phrase and the phrase itself, and is likely due to the semantic incorporation of information mediated by spatial imagery).

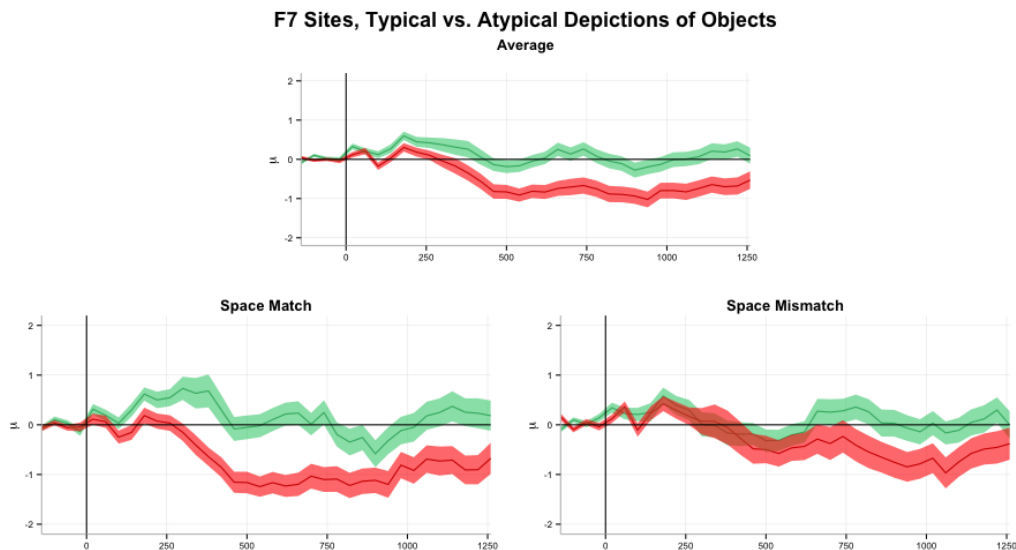


Figure E.5: Responses to nouns after atypical (red) and typical (green) pictures in F7 sites for all nouns (top), spatial match nouns (bottom left) and spatial mismatch nouns (bottom right).

Therefore, these results simply provide evidence that the spatial configuration of objects presented in pictures had a stronger and more consistent influence on responses to reference nouns in concrete spatial phrases than other possible factors,

like typicality.

## **E.4 Responses to *In* versus *On***

There is a fairly robust relative negativity in medial central and parietal regions (Cz and Pz) that peaks between 350-400ms after the onset of *on* after participants have seen a picture of an object in an *in* configuration (compared to responses after seeing pictures of objects in spatially matching, *on*, configurations), see Figure E.6b and Figure E.6c. This is not true for *in* phrases. In fact, the opposite pattern occurs- so that responses to *in* is more negative in medial central and parietal regions after seeing objects in *in* configurations, see Figure E.6e and Figure E.6f.

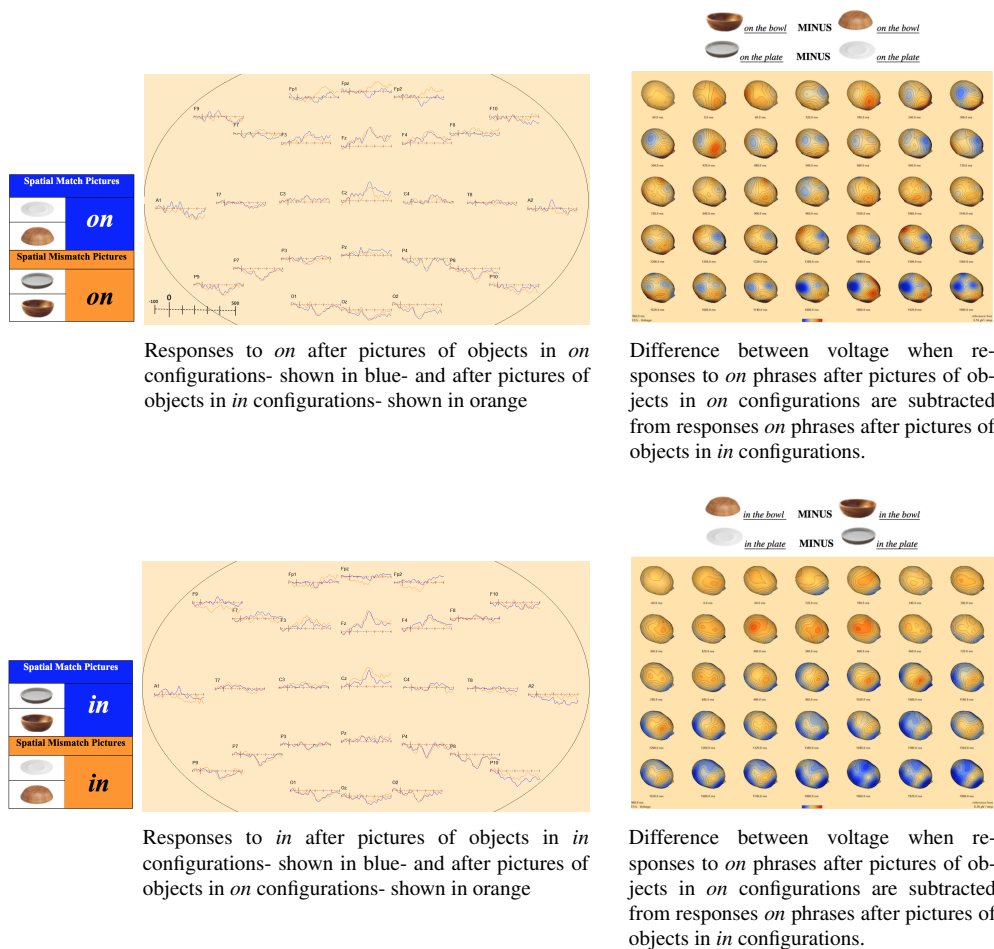


Figure E.6: Responses to prepositions and prepositional phrases headed by *on* (top) and *in* (bottom) after spatially matching and spatially mismatching pictures.

It was unexpected that reading one preposition (i.e., *on*) would yield an N400 response after seeing pictures of objects in spatially mismatching configurations and the other would not (i.e., *in*). This result- that a relative N400 response was elicited by reading *on* after seeing pictures of objects in *in* configurations, but not for the opposite case, when *in* was read after seeing pictures of objects in *on*

configurations- has a few interpretations:

1. That *on* pictures were better at priming the preposition *on* than *in* pictures were at priming the preposition *in*
2. That *on* pictures were just as effective at priming the preposition *in* as *in* pictures. And, perhaps *on* pictures were even more effective at priming *in* than *in* pictures were, since there is a relatively larger negativity to *in* after *in* pictures than *on* pictures.
3. That this negativity is not an N400 response at all, and is instead a negativity to the *in* pictures (relative to the *on* pictures), which persists through the first few words of the phrase.

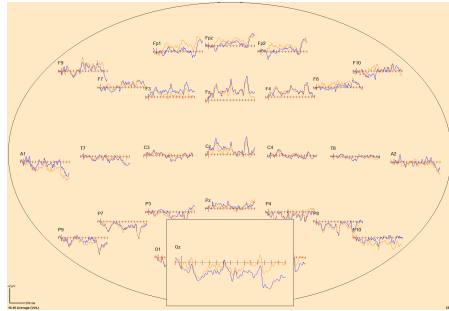
The timing of the peak (between 350 and 400 milliseconds post-preposition onset) and its location (in medial central and parietal regions) are typical of an N400 response<sup>1</sup>, it is believed that one of the first two interpretations are more likely. Further, responses to both *in* and *on* after seeing pictures of random objects (whose spatial configurations were not a match for either *in* or *on*) yielded a relative negativity at the same time and in the same region as the one found to *on* after seeing photographs of objects in *in* configurations (See Figure E.7).

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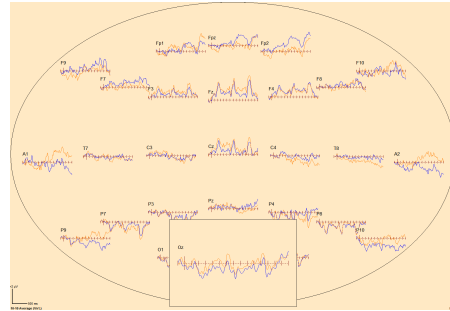
<sup>1</sup>This peak's morphology is identical to the N400 response seen to reference nouns in spatially inappropriate frames, *in the plate*, which provides more support that this response is an N400 effect.







(a) Responses to *on* after pictures of objects in *on* configurations- shown in blue- and after pictures of objects in *in* configurations- shown in orange



(b) Responses to *in* after pictures of objects in *in* configurations- shown in blue- and after pictures of objects in *on* configurations- shown in orange

Figure E.8: Responses highlighting occipital negativities to prepositions *on* (left) and *in* (right) after spatially matched pictures as compared to responses after spatially mismatched pictures.

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