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152303

Semantic processing in the native and non-native language: The role of working memory and the type of semantic relations

Przetwarzanie semantyczne w języku rodzimym i obcym: Rola pamięci roboczej oraz rodzaju powiązań semantycznych

Rozprawa doktorska napisana
na Wydziale Anglistyki
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pod kierunkiem Prof. Waltera van Heuvena
oraz dr Karoliny Rataj

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OŚWIADCZENIE

Ja, niżej podpisany

Dmytro Khanzhyn

przedkładam rozprawę doktorską

pt. Semantic processing in the native and non-native language: The role of working memory and the type of semantic relations
(Przetwarzanie semantyczne w języku rodzimym i obcym: Rola pamięci roboczej oraz rodzaju powiązań semantycznych)

na Uniwersytecie im. Adama Mickiewicza w Poznaniu

i oświadczam,

że napisałem ją samodzielnie.

Oznacza to, że przy pisaniu pracy, poza niezbędnymi konsultacjami, nie korzystałem z pomocy innych osób, a w szczególności nie zlecałem opracowania rozprawy lub jej istotnych części innym osobom, ani nie odpisywałem tej rozprawy lub jej istotnych części od innych osób.

Jednocześnie przyjmuję do wiadomości, że gdyby powyższe oświadczenie okazało się nieprawdziwe, decyzja o wydaniu mi dyplomu zostanie cofnięta.

Poznań, 19/06/2023
(miejscowość, data)

Khanzhyn
(czytelny podpis)

Table of contents

List of tables

List of figures

Introduction

The study of meaning has been in the focus of psycholinguistic and cognitive research for the last several decades. One of the challenges is that meaning is an abstract notion that cannot be immediately observed in the objective world – it can only be investigated by indirect means, language being one of the most powerful ones. Numerous theoretical models (Collins and Quillian 1969; Smith et al. 1974; Tversky 1977; Lund and Burgess 1996; Collins and Loftus 1975; Landauer and Dumais 1997; De Deyne and Storms 2008; Vigliocco et al. 2009; Mikolov et al. 2013) have been proposed to explain the structure of semantic memory and relations between words and meanings. These models have different perspectives on how meanings are linked together, but what they all agree on is that some words in language are related, and others are unrelated, or less related. The nature of these relations, their connection to working memory, and their implications for language processing will be the focus of this doctoral thesis.

The main aim of three studies described in this thesis was to investigate the role of working memory and different types of semantic relations in semantic processing in the native and non-native language. Study 1 focused on the distinction between associative and semantic relations in a set of Polish stimuli (Rataj et al. 2023). It provided experimental evidence that the tested word pairs were predominantly linked by semantic rather than associative relations. It is important because the same materials were used in Study 2 to investigate how semantic processing can be influenced by verbal and spatial working memory load. Study 2 included three behavioural experiments that focused on the impact of different types of working memory load on semantic relatedness judgements of word pairs with different degrees of semantic relatedness. While Study 1 and Study 2 were conducted in participants' native language, Study 3 explored the differences between native and non-native language processing. Its main objective was to explore how semantic relatedness judgements of symmetrically and asymmetrically associated words differ in native and proficient non-native speakers.

This doctoral thesis consists of three parts: Chapters 1 and 2 provide a theoretical background and an overview of literature relevant to the topic, Chapters 3–5 present three empirical studies, and Chapter 6 interprets the experimental results, discusses them in the context of previous findings and theoretical models, and presents potential limitations and avenues for future research.

Chapter 1 outlines the theoretical framework for the experimental studies. First, it reviews different approaches to the study of semantic memory along with their strengths and weaknesses. Further, it introduces the phenomenon of semantic priming, which provides a window into semantic representations and is a widely used paradigm in word meaning research (Neely 1976; McNamara 2005). The chapter next focuses on several theoretical aspects of semantic processing that will be relevant for the experimental studies and highlights several significant empirical studies from the field. Furthermore, it provides a rationale for the research questions posed in the thesis and for using the research methods that are specified in each of experimental chapters.

The focus of Chapter 2 is on working memory, which is one of the executive functions that is inseparable from our ability to learn and use a language. Several influential models of working memory (Baddeley and Hitch 1974; Baddeley et al. 2020; Cowan 1988, 1999; Barrouillet and Camos 2007, 2020) are presented and critically evaluated in terms of their advantages and limitations. The chapter next discusses how working memory is linked to our linguistic abilities (Gathercole 2007; Wen 2019; Martin 2021) and presents several studies exploring the distinction between spatial and verbal working memory, which is central to the experimental study reported in Chapter 4, as well as the influence of working memory on other cognitive functions.

Chapter 3 presents an online Polish word association study (Study 1). It was the first experimental study conducted within this project, and its aim was twofold. First, association norms were developed for a set of Polish stimuli from a previous study (Rataj et al. 2023). In the original study, the stimuli were analysed in terms of semantic, but not associative relations. It is however known from the literature (Lucas 2000; Xavier Alario et al. 2000; Perea and Rosa 2002; Hutchison 2003; Ferrand and New 2004) that associative relations, which are based on the co-occurrences of words in a language, and semantic relations, which are based on meaning overlap, may play a different role in language processing. Because the same stimuli were later used in Study 2, which focused on semantic processing, it was important to understand the nature of relations between words in critical word pairs. To this aim, association responses collected in Study 1 were compared with semantically related words from Rataj et al. (2023). Second, the human-obtained association measures were correlated with a corpus-based measure of semantic relatedness. There is some evidence that association data can explain human performance on semantic tasks (De Deyne et al. 2019) and that corpus-based word vectors can represent semantic relations (Landauer and Dumais 1997; Mikolov et al. 2013; Mandera et al. 2017). To establish the relation between word associations and semantic vectors, the obtained measures of associative relatedness were compared with semantic similarity values obtained from semantic spaces (Mykowiecka et al. 2017).

Study 2 reported in Chapter 4 encompasses three reaction time experiments involving the semantic relatedness task. The main aim of Study 2 was to investigate the influence of spatial and verbal working memory load on the processing of word pairs with different degrees of semantic relatedness. There is some evidence that semantic processing may involve strategic mechanisms (Neely and Kahan 2001) and depend on executive functions (Hutchison et al. 2014; Heyman et al. 2015; Radel et al. 2015). However, previous research on the impact of working memory did not distinguish between spatial and verbal domains or between semantically strongly and weakly related pairs (Heyman et al. 2015, 2017). On the other hand, other studies (Kuperberg et al. 2008; Ortu et al. 2013) used the intermediate relatedness condition in a semantic relatedness task, but they did not study the effect of working memory. To fill this gap in research, in Experiment 2.1 participants performed a dual task in which a semantic relatedness judgement task was interleaved with a spatial or verbal working memory task. Experiments 2.2 and 2.3 were control experiments without the working memory task that differed in terms of procedure. The materials for this study were taken from Rataj et al. (2023) and further verified in Study 1 to make sure that word pairs were related semantically rather than associatively.

Chapter 5 presents Study 3 that included two experiments aimed to explore the differences in relatedness judgements in the native and non-native language. Non-native speakers may process meaning differently as compared to native speakers (Frenck-Mestre and Prince 1997; Phillips et al. 2004; Ankerstein 2014) and engage additional executive resources to control their two languages (Altarriba and Basnight-Brown 2007; Thierry and Wu 2007; Bialystok 2009). At the same time, it was found that different strategies may be involved in the processing of related word pairs with different types of association (Thomas et al. 2012; Hutchison et al. 2014; Heyman et al. 2015, 2017). Study 3 investigated relatedness judgements of words with different types of association in the native and non-native language. Both experiments used the same English stimuli adapted from Thomas et al. (2012), but participants were native speakers in Experiment 2.1 and non-native speakers in Experiment 2.2.

Finally, Chapter 6 presents a detailed discussion of each of the experimental studies along with their potential limitations and suggestions for further research. The key findings of the present thesis provided insight into the role of working memory and different types of semantic relations in semantic processing in the native and non-native language. In the last chapter, these findings are interpreted in the context of previous research reviewed in Chapters 1 and 2. Chapter 6 also links the three experimental studies together, summarises implications of the results for relevant theories and models, and describes the contribution of the findings to the knowledge about semantic processing.

Chapter 1: Lexico-semantic processing and semantic priming

1.1. Introduction

This chapter introduces the main theoretical notions that will be of relevance for this dissertation and presents the state of art in the field of lexical semantics – the study of words and meanings. Words are basic meaningful elements of every language, but how their meanings are learned, updated and retrieved from memory is a subject of extensive scientific research. This chapter begins with presenting several influential models of meaning representation along with their advantages and limitations. A widespread method of investigating relations between concepts in semantic memory is the semantic priming paradigm. Its main tenets and models are discussed further in the chapter. Next, the chapter focuses on several aspects of semantic priming that are relevant for the experimental studies conducted within this thesis. In particular, the distinction between word-based associative relations and concept-based semantic relations is important for Study 1 (Chapter 3), which tested whether semantically related Polish words (Rataj et al. 2023) also showed associative relations. This distinction was previously investigated in several influential studies that are summarised in Section 1.3.2. The chapter further focuses on the role of executive functions in semantic processing to provide a theoretical background for Study 2 (Chapter 4), which investigated the impact of working memory load on semantic processing. Executive resources may be particularly taxed in a non-native language (Szmalec et al. 2012), which may result in differences between native and non-native semantic processing. Several experimental studies that explored semantic priming effects in different language conditions are described in Section 1.3.4. It is relevant for the present thesis because Study 3 (Chapter 5) investigated whether word pairs with different types of association are processed differently in the native and non-native language. Finally, this chapter includes a discussion and use cases of the semantic relatedness task – one of the methods of investigating semantic processing. This task involves conscious meaning processing of both words in a pair, so it is likely to be more suitable for studying the effects of working memory and strategic mechanisms on semantic processing and was used in Studies 2 and 3. Overall, the chapter provides comprehensive theoretical groundwork for the three experimental studies reported in Chapters 3–5.

1.2. Lexical semantics and representation of meaning: models of semantic memory

In our everyday life, we are constantly trying to make sense of objects and ideas around us, and we use words to communicate meanings and exchange knowledge about the world. But how do we know what the word *water* stands for? Does it mean the same as *woda* in Polish or *вода* in Ukrainian or Russian? Nothing in the word itself suggests its meaning and there is no one-to-one correspondence between the form of the word and the concept that it represents. In linguistics and cognitive science, the study of word meaning is known as lexical semantics, and it is concerned with understanding how words are organised in the mental lexicon and how they relate to one another. The knowledge of word meanings is an integral part of semantic memory, which also encompasses memory for facts, concepts, and general world knowledge (Jones et al. 2015).

Despite the fact that word meanings are almost instantaneously deciphered by speakers of a language, it is still unclear how word representations are learned, stored in and retrieved from semantic memory. How do we know that *dog* is more closely related to *cat* than to *table* although they all usually have four legs? Is it because dogs and cats share more features than dogs and tables – aside from having four legs, both dogs and cats have fur and can jump, but tables cannot? Or is it because dogs and cats belong to the same category of pets, and table does not? Or is it because dogs and cats more frequently appear in the same context than dogs and tables? Can relations between words and meanings be calculated and inferred based on large collections of texts? These and numerous other questions are addressed by different models of semantic memory, some of which are presented below.

1.2.1. Attributional, or feature-based models of semantic memory

Feature-based models of semantic memory suggest that word meaning is represented as a set of features or attributes (hence the alternative name "attributional") that describe the properties of a concept (Meteyard and Vigliocco 2018). These models propose that the mental representation of a word is constructed from the activation of specific attributes, such as size, shape, colour, etc., that are associated with the concept. In these models, the meaning of a word is not represented as a single, unified representation, but as a combination of its feature-based representations. Features can be defining, i.e. shared by several concepts, or characteristic, i.e. unique for particular concepts (Smith et al. 1974). For example, *dog* will have defining features <has legs>, <has fur>, and <can jump>, and a characteristic feature <can bark>. In contrast, *table* will be described by defining features <has legs>, <is made of wood>, and a characteristic feature <can be sat at>. The degree of similarity between concepts can then be explained by the proportion of overlapping to distinctive features. According to feature-based models, *dog* will be more closely related to *cat* because these concepts share many attributes, than to *table*, which has fewer overlapping features (Tversky 1977).

The general theoretical framework of feature-based meaning representation was laid by early models (Smith et al. 1974; Tversky 1977), but it was not until more recent studies that this approach gained some empirical evidence (e.g. McRae et al. 1997; Vigliocco et al. 2004; McRae et al. 2005). For example, McRae et al. (1997) asked participants to generate multiple features for a set of concrete nouns. As a result, they developed feature norms, which presumably reflected participants' semantic representations, and calculated correlations between individual features. Continuing this line of research, McRae et al. (2005) conducted a similar study on a much larger scale, collecting semantic features for 541 living and non-living concepts from 725 participants. The resulting data were made publicly available and were analysed, among others, in terms of feature saliency, feature correlations and brain region taxonomy. Notably, feature distribution analysis was also performed and similarity between concepts was calculated based on cosines between values in a concept-by-feature matrix. As described in more detail in Section 1.2.3, a similar approach will later be used in corpus-based computational models of semantic memory.

One of the advantages of feature-based models is that they can readily account for non-linguistic input from different modalities, such as vision, hearing, and touch (Meteyard and Vigliocco 2018). For instance, the attributes of *cat* can include the acoustic representation of the purring sound, the visual representation of cats, and the tactile representation of stroking a cat. Such multimodality of features is in line with theories of embodied cognition (Meteyard et al. 2012) that emphasise the importance of the body and its interactions with the environment in shaping cognitive processes and semantic representations. The embodiment perspective suggests that the meaning of language is not simply represented by abstract symbols but is instead grounded in our bodily experiences and interactions with the physical world.

Furthermore, because feature-based models allow for the representation of a variety of features, they can account for a wide range of semantic relationships that exist between words, including both similarity and dissimilarity, as well as the graded nature of semantic similarity (McRae 2004; Vigliocco et al. 2004). Additionally, these models have been quite successful at explaining various behavioural effects in different populations (Farah and McClelland 1991; McRae 2004). For example, the measures of feature correlation have been shown to predict performance in typicality and living/non-living judgement tasks (McRae et al. 1997; Vigliocco et al. 2004), and to account for the semantic priming effects between concepts referring to superordinate categories and category members (exemplars) (Cree and McRae 2003; Vigliocco et al. 2004).

On the other hand, there are certain limitations inherent in all feature-based models. First, they struggle with explaining how all semantic features of a concept converge to form one coherent representation (Meteyard and Vigliocco 2018). It is not clear how features stemming from different modalities and contexts can be integrated into what we call word meaning. This becomes particularly challenging in the case of abstract or fictional notions, such as *freedom* or *elf*, which do not have clear referents in the objective world. Added to this limitation is the fact that most of empirical property-generation studies focused on collecting attributes of concrete nouns, whose representations are multimodal and grounded in our everyday experience (although there were attempts to develop norms for action nouns and verbs (Vigliocco et al. 2004)). Second, feature-based models do not provide an explanation of how people learn semantic features and relations between concepts (Kumar 2021). Empirical property-generation studies (McRae et al. 1997; McRae et al. 2005) have shown that most salient features of basic concepts are shared among language speakers, and this is understandable because people need to agree on the meaning of the words for successful communication. But how do we come to know what *dog* or *freedom* means? And how do all speakers of a language achieve a common understanding that <has four legs> is a feature of *dog* rather than *freedom*? This developmental aspect is not sufficiently addressed by feature-based accounts of semantic memory. Despite these limitations, feature-based models have significantly contributed to the understanding of semantic representations and provided solid ground for the development of distributional semantic models.

1.2.2. Network-based models of semantic memory

In parallel with feature-based accounts of semantic memory, which represent the meanings of words in terms of features or attributes, other models were developed that viewed semantic memory as a complex network of interconnected nodes. This network-based approach was pioneered by Collins and Quillian (1969) who proposed a hierarchical structure of concepts and semantic propositions: e.g. *dog* would be linked to the superordinate concept of *animal* and characterised, for example, by the proposition <can bark>. The relationships between two individual words or propositions in this model can be described by the number of links between them. The activation of one node leads to the activation of immediate neighbours and then propagates across the entire network until the other word is “retrieved”. This model could explain differences in time needed to make a decision about the veracity or falsity of sentences, but it could not account for typicality effects when some words (e.g. *sparrow*) are recognised as instances of a particular category (birds) faster than others (e.g. *goose*). The initial hierarchical model was later reworked into a more horizontal structure (Collins and Loftus 1975) allowing any two words to be linked together. The activation of nodes in the revised model depended on the strength of the links between concepts (Fig. 1). This idea of activation propagation and various connection strengths crystallised into the spreading activation framework, which became highly influential in different areas of cognitive sciences and has been widely used to explain various linguistic and cognitive phenomena, such as semantic priming, lexical decisions, and associative memory (McNamara and Altarriba 1988; Neely and Kahan 2001; Hutchison 2003; McNamara 2005). The implications of the spreading activation approach to semantic priming will be discussed in more detail in Section 1.3.

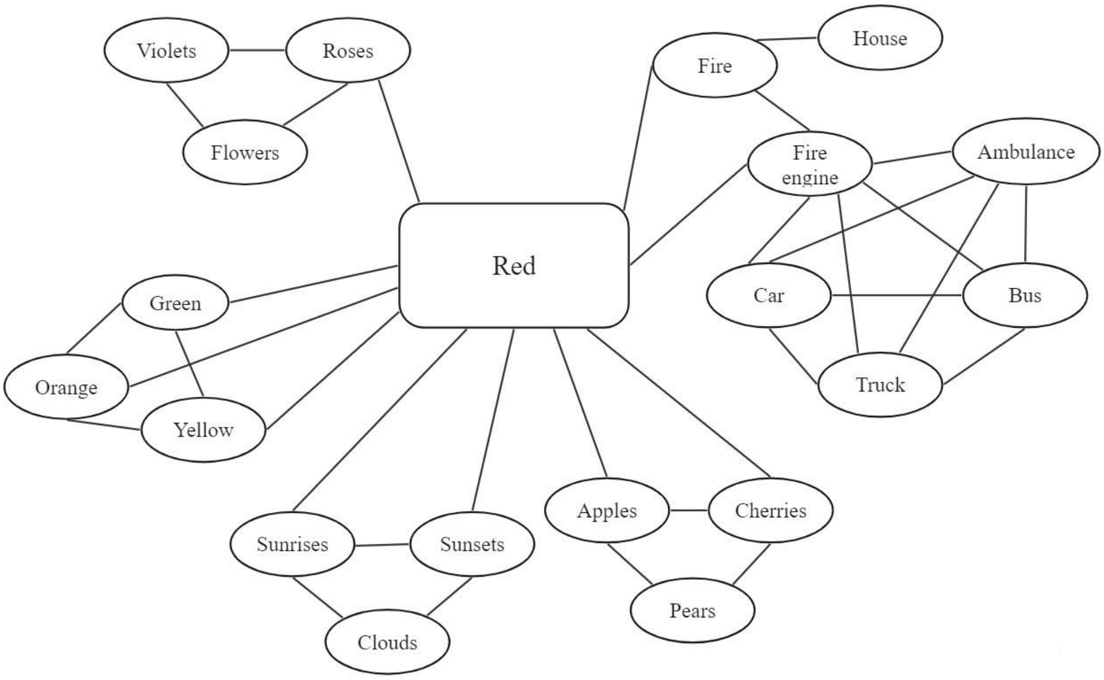

Fig. 1. A schematic representation of concept relatedness in a fragment of human memory (adapted from Collins and Loftus 1975).

Another example of a large-scale model of meaning representations is WordNet (Miller 1992, 1995). It is an online lexical database, in which “English nouns, verbs, adjectives, and adverbs are organized into sets of synonyms, each representing a lexicalized concept” (Miller 1995:39). The words are linked by various semantic relations, such as synonymy (similar-to), antonymy (opposite-to), hypernymy (is-a), meronymy (part-of), or entailment (implies). Each word is connected to other words with which it shares some semantic relationship, forming a complex semantic network. This hierarchical structure allows for efficient search and retrieval of information about word meanings and relationships, making WordNet a valuable tool for a wide range of computational and lexicographic applications.

In contrast to early semantic and lexical networks, which focused on describing the general structure of semantic memory and relations between words, word association studies have used real-life data to investigate the associative structure of mental lexicon. In this type of studies, participants are usually presented with a word (the cue) and asked to generate a response (the target) that is associated with the cue in some way. These associations can then be categorised based on a number of factors, such as the strength of association, direction (e.g. forward or backward), and the type of relationship (e.g. semantic, phonological, or conceptual).

In English, there have been several attempts to collect and develop word association norms, dating back to more than a hundred years ago (Kent and Rosanoff 1910). One of the first interactive associative thesauri was the Edinburgh Associative Thesaurus (EAT; Kiss et al. 1973), which consisted of 100 responses per cue for 8,400 cue words. Another commonly used collection of English associative norms is the University of South Florida (USF) norms (Nelson et al. 1998, 2004) that include responses to over 5,000 cues from more than 6,000 participants. The USF norms are publicly available and provide, among others, word statistics, measures of forward and backward association strength and most frequent responses to each cue (Nelson et al. 2004).

The development of relatively large association databases and a general interest in computational graph-based data models led researchers to view semantic memory as a small-world structure (De Deyne et al. 2016; Steyvers and Tenenbaum 2005). Small-world structures are complex networks that exhibit both local clustering and global connectivity. They are characterised by the presence of densely connected clusters of nodes, which are interconnected through a small number of highly connected hubs. The small-world network architecture has been observed in a variety of real-world systems, including social networks, the Internet, brain networks and genetics (Watts and Strogatz 1998; Barabási and Albert 1999; De Deyne and Storms 2008; Telesford et al. 2011).

Building on the assumptions of small-world network theories, a large-scale project called “Small World of Words” (https://smallworldofwords.org/) was launched with the aim of mapping the human lexicon through associations in major world languages. It is a crowdsourced project led by Dr. Simon De Deyne and Prof. Gert Storms and involving several research teams from all over the globe with an aim of collecting association norms in different languages. The project currently includes 18 languages with the most numerous datasets obtained for Dutch and English. DeDeyne et al. (2019) reported and generalised results for over 12,000 English words, to which associations from over 90,000 participants were collected over 7 years. A distinctive feature of their approach was that they asked participants to produce three responses to each cue word, which allowed for the detection of weaker associative links. The resulting network metrics demonstrated that the new norms had a higher explanatory power compared to USF and EAT measures and effectively predicted human performance on semantic tasks, such as similarity judgements.

Although the Small World of Words project is multilingual, it does not include the Polish language. Previously, there have been several attempts to develop association norms in Polish, but they were quite limited in terms of stimulus words and the number of participants. The first available word association study in Polish was conducted by Kurcz (1967) whose cue words included Polish translations of Kent and Rosanoff's (1910) list of 100 words. The study involved 1000 students from Warsaw who were asked to provide as many responses to the cue words as they could come up with. Another association study by Gawarkiewicz et al. (2008) involved 500 participants who provided responses to 110 words. The aim of their ethnolinguistic study was to compile a Polish association dictionary and compare association networks in Polish and Russian. Both Kurcz's and Gawarkiewicz et al.'s studies were administered as pen-and-paper tasks and provided only scarce information about cue-target relations. The largest and the only available computer-based association network in the Polish language was developed by Izabela Gatkowska (Gatkowska 2015, 2016). She used selected nouns from Kurcz's (1967) list as primary stimuli and added the most frequent responses from that experiment as secondary stimuli, which resulted in a total of 322 cue words that included nouns, adjectives and verbs. The experiment involved 900 participants who typed in only their first association to the stimulus words within a five-second time frame. The resulting responses were connected in an association network comprising 11,224 lexical nodes and more than 50,000 in- and outgoing links between them. However, this dataset represents only a small share of an average speaker's vocabulary and is far scarcer than those collected in the Small World of Words project. In the present project, word associations were used to check whether semantically related Polish word pairs from a previous study (Rataj et al. 2023) are also related associatively. Because association norms for these words were not available, a separate word association study was conducted, which is described in detail in Chapter 3.

An advantage of network-based models is that they provide a holistic view of the semantic memory capturing relations between multiple concepts and categories. The structure of semantic networks and the idea of spreading activation between nodes can explain many cognitive phenomena, such as semantic priming and semantic relatedness. At the same time, network parameters can be quantified and can serve as effective predictors of performance on various linguistic activities, including lexical decision, semantic decision, and naming tasks (De Deyne et al. 2019). Furthermore, associative networks which are based on a large number of responses reflect language users' worldview and are therefore grounded in everyday experiences rather than being confined to the language itself.

However, network-based models of semantic memory struggle with the same limitations as feature-based models. Whereas they describe the structure of mental representations, they can hardly explain how these representations were created and how new connections are formed in the mental lexicon (Kumar 2021). Another criticism specific to associative networks stems from the fact that responses are always generated in response to a certain cue, so the associative structure may reflect lexical or semantic retrieval-based processes rather than the organisation of the semantic memory itself. Furthermore, in word association studies that collect several responses to the same cue, subsequent responses may be triggered by the previous response rather than the cue itself (Nelson et al. 2004; De Deyne et al. 2019). These limitations are addressed by more recent computational models of semantic memory that will be discussed in the following section.

1.2.3. Computational semantic models and semantic vectors

With the advent of digital corpora, i.e. large collections of natural linguistic data, and new algorithms for the processing of this data, a new group of semantic memory models has emerged that became known under the umbrella term of distributional semantic models. They postulate that words can be represented by the patterns of co-occurrences with other words in large text corpora and that the meaning of a word can be inferred from the distribution of its co-occurring words. In simple terms, distributional semantic models hold that words that appear in similar contexts should have similar meaning; conversely, specific contexts will restrict or even determine word meaning (Günther et al. 2019). Because text corpora operate with large amounts of data, word representations can be mathematically quantified. The contexts in which the word appears can be represented as dimensions, and words can be represented as numerical vectors (also called word embeddings) populating a high-dimensional semantic space. The relations between word representations can then be reduced to relations between vectors which will follow the same mathematical laws that apply to vector spaces in general. For example, words with similar meanings will be represented by similar vectors that will be located close to each other in a semantic space. The underlying principle of representing meaning based on word co-occurrences is common for numerous distributional models that have been developed over the last decades although they use different approaches to determining contexts, calculating word vectors and incorporating new word representations.

One of the first distributional semantic models was the Hyperspace Analogue to Language (HAL) developed by Lund and Burgess (1996). They processed a text corpus and calculated word co-occurrences within a window of five to ten words. A smaller co-occurrence strength was assigned to words that were farther apart within the window. By moving the window along the corpus, the researchers constructed a co-occurrence matrix including all words appearing in the database. The authors of the model demonstrated that word representations in this matrix provided semantic information rather than simply a measure of lexical co-occurrence, i.e. words that were similar in meaning but rarely co-occurred in texts tended to have similar vectors. Distances between HAL-derived semantic vectors were also shown to correlate with results in associative and semantic priming tasks (Lund and Burgess 1996).

Another widely recognised and frequently cited distributional semantic model based on calculating word vectors is the Latent Semantic Analysis (LSA) model (Landauer and Dumais 1997; Landauer et al. 1998). Whereas the HAL model analysed co-occurrences within a narrow window of words, LSA matrices represented how frequently a word appeared in each document in a corpus. The LSA model further employed log transformation of frequencies and a dimensionality reduction technique to generate semantic representations. These two major improvements allowed LSA vectors to account for relations between words across different texts and capture additional semantic information that could not be extracted from direct lexical co-occurrences.

A similar approach of creating word matrices was used in several other models that differed in terms of co-occurrence patterns, transformation parameters and dimensionality reduction techniques, e.g. latent relational analysis (LRA, Turney 2006), topic models (Griffiths et al. 2007) or Bound Encoding of the Aggregate Language Environment (BEAGLE, Jones and Mewhort 2007) (see Lenci 2018; Günther et al. 2019 for an overview). They are all based on the idea of counting word co-occurrences in predefined text corpora, so they came to be described as count models (Baroni et al. 2014; Mandera et al. 2017). A potential limitation of this approach is related to its psychological plausibility: count models require large collections of available linguistic data and considerable computational resources to calculate word vectors, and this does not resemble the way people understand language (Günther et al. 2019). Indeed, we do not need to process the entire information about word co-occurrences to quickly understand the meaning of a new word. Furthermore, the training of count models involves error-free learning mechanisms (Kumar 2021), which result in static representations. In order to expand the dataset or adjust the vector values, the entire model needs to be re-trained. In the real world, however, word meanings are constantly modified under the influence of our experience or changing environment.

Recently, a new generation of distributional semantic models has appeared, which have been termed prediction-based, or predict models (Baroni et al. 2014; Mandera et al. 2017; Günther et al. 2019; Kumar 2021). They use neural networks with hidden layers to predict output using error-driven learning mechanisms. The learning occurs incrementally by constantly re-adjusting connection weights between network nodes. One of such predict models that has become very popular both in computational and cognitive linguistics is *word2vec* (Mikolov et al. 2013). The model has two architectures (see Fig. 2): the continuous bag-of-words (CBOW) model predicts the target word from the context (e.g. in the sentence *With great power comes great responsibility* it predicts the word *power* given the context *With great ___ comes great responsibility*), whereas the skip-gram model predicts the context from the current input (e.g. given *great power comes great*, it predicts the rest of the sentence). There has been some evidence that predict models mostly outperform count models in a variety of psychological and linguistic tasks (Baroni et al. 2014; Mandera et al. 2017) and that these models present a more human-like mechanism of meaning representation (Lazaridou et al. 2017).

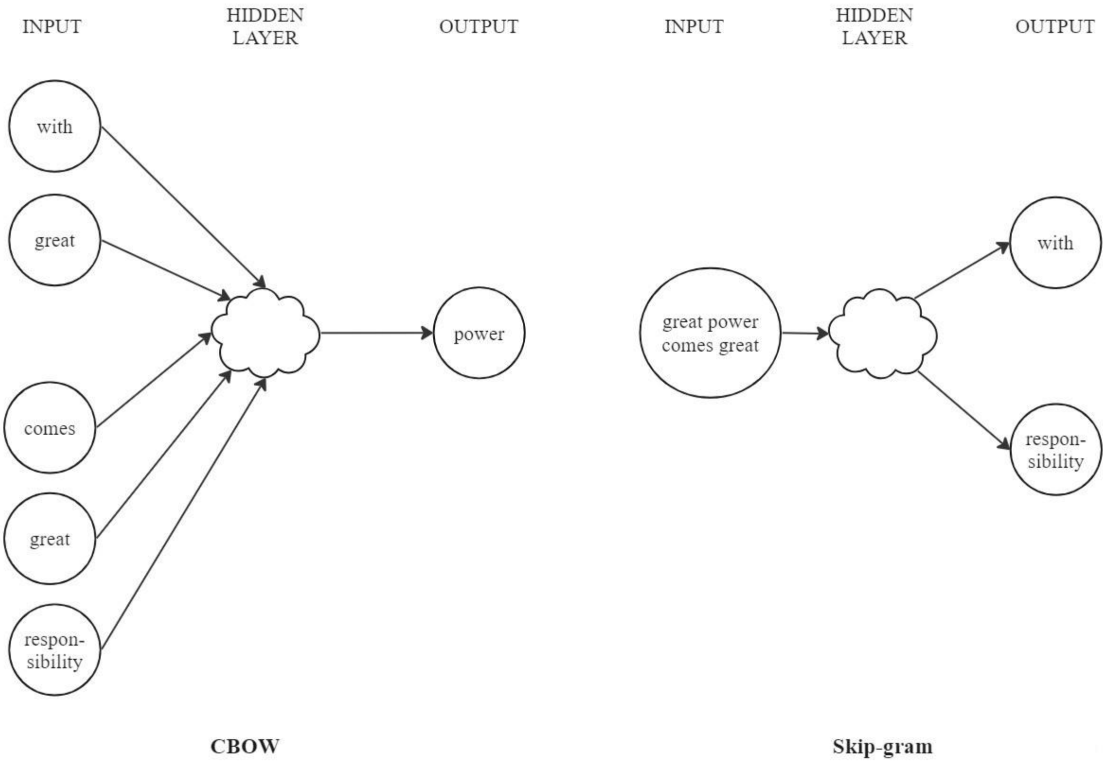

Fig. 2. *Word2vec* model architectures (adapted from Mikolov et al. 2013).

There is however no single model that would ideally fit every task in every language. The model training process and the resulting semantic spaces may vary on a number of parameters from the type of corpus used to the number of hidden layers to the number of dimensions for each vector. The choice of the best-fitting model will thus depend on its ability to predict results in a particular task (Mandera et al. 2015a, 2017; Mykowiecka et al. 2017; Rataj et al. 2023). As is the case with association databases, both large datasets of behavioural data (Balota et al. 2007; Keuleers et al. 2015; Hutchison et al. 2013) and well-tested semantic spaces (Mandera et al. 2017) are available for the English language, but the data are much more limited for other languages, including Polish. One large-scale distributional semantics project in Polish was undertaken by Mykowiecka et al. (2017), who developed and made publicly available (http://dsmodels.nlp.ipipan.waw.pl/) a number of semantic spaces that use different combinations of corpora and hyperparameters. These semantic spaces were used by Rataj et al. (2023) to select semantically strongly related (e.g. *hip – KNEE*), weakly related (e.g. *muscle – KNEE*), and unrelated (e.g. *office – KNEE*) word pairs for their study on semantic processing. The word pairs selected with semantic spaces were further evaluated by independent judges and tested in a rating study to generate a final stimulus set for a behavioural experiment. The stimuli were then used in a semantic priming lexical decision task, which revealed a significant facilitation effect for both strongly and weakly related pairs, but the magnitude of this semantic priming effect was much stronger for the former (31 vs 14 ms, see Fig. 3). Furthermore, the authors trained a new set of semantic spaces in Polish and proposed a methodology for comparing multiple semantic spaces and selecting the best-fitting model capable of predicting semantic priming effects in a behavioural study.

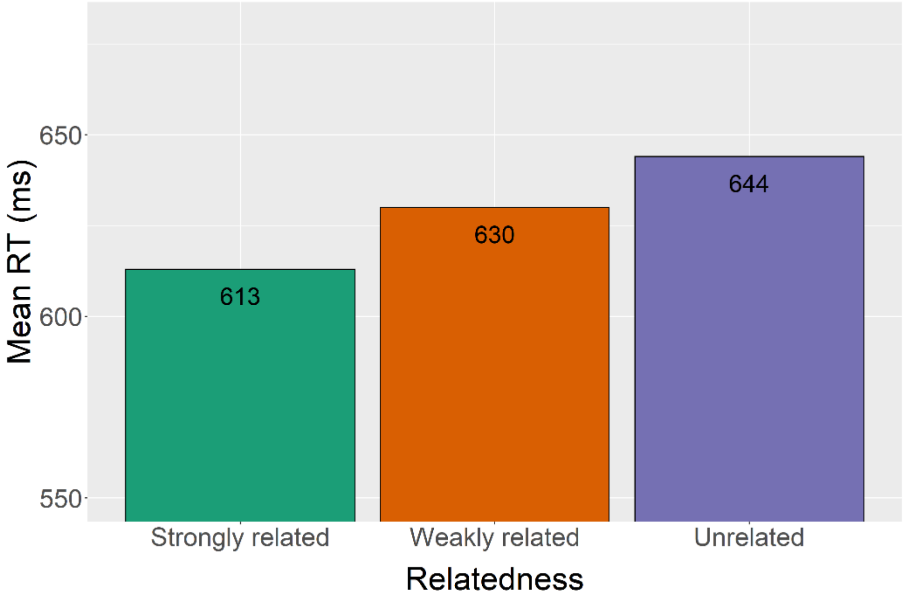

Fig. 3. Mean reaction times as a function of prime-target relatedness in Rataj et al.'s (2023) semantic priming lexical decision experiment (adapted from Rataj et al. 2023).

In the present project, semantically related word stimuli developed by Rataj et al. (2023) were further investigated for associative relations in Study 1 (see Chapter 3). Polish semantic spaces (Mykowiecka et al. 2017; Rataj et al. 2023) were used in this study to compare human-obtained association data with corpus-based measures of semantic similarity. The materials from Rataj et al. (2023) were then used in Study 2 (see Chapter 4) to explore the influence of working memory type and load on semantic processing in a semantic relatedness task. Furthermore, Study 3 (see Chapter 5) compared semantic processing with words in the native and non-native language, and English semantic spaces were used to provide additional information about semantic similarity for a dataset of word pairs with different types of association.

1.3. Semantic priming paradigm and its role in semantic processing

One of the most popular experimental paradigms to investigate meaning representations is semantic priming. It refers to a well-established finding in the literature that people are faster and more accurate at recognizing target words (e.g. *coffee*) that are preceded by semantically or associatively related primes (e.g. *tea*) relative to unrelated primes (e.g. *sky*) (Neely 1976, 1991; McNamara 2005). This facilitation effect was first reported by Meyer and Schvaneveldt (1971) and has been studied extensively afterwards. One of the advantages of the semantic priming paradigm is that the facilitation effect is consistently observed across different lexical and semantic tasks (Lucas 2000; Hutchison 2003; Hutchison et al. 2013), across different modalities (Anderson and Holcomb 1995; Bentin et al. 1995), both in speech recognition and speech production (Xavier Alario et al. 2000), in different languages and between languages (Basnight-Brown and Altarriba 2007), with different stimulus onset asynchronies (SOA, i.e. intervals between the presentation of primes and targets) (de Groot et al. 1986) and even when participants do not consciously see the prime. When the prime word appears only for a short interval (e.g. <60 ms) and it is masked (preceded and/or followed by a mask before the target is presented) so that participants are not aware of its presentation (de Groot et al. 1986; Neely 1991), the paradigm is referred to as masked priming.

1.3.1. Models of semantic priming

The ubiquity of the semantic priming effect led researchers to develop several models explaining the effects of relatedness between primes and targets. Many of these models have strong links with more generic accounts of semantic memory discussed above. For example, the localist spreading activation model of semantic priming (Collins and Loftus 1975) echoes the early network-based model of semantic memory (Collins and Quillian 1969) and posits that concepts are represented in a network of nodes, and the connections between nodes represent the strength of the association between those concepts. When a node is activated, this activation spreads along the connections in the network, activating related nodes. Collins and Loftus (1975) distinguished between two closely intertwined structures: the semantic network with meaning representations (concepts) as nodes, and the lexical network with the nodes constituted by form representations (phonemic or orthographic). In the context of semantic priming, the spreading activation model holds that when a person encounters a word, e.g. *dog*, related concepts, such as *cat* or *pet*, also get pre-activated and can then be recognised and processed faster than an unrelated word, e.g. *table*. One of the key features of the spreading activation model is the notion of activation decay. According to this theory, the strength of activation of a node decreases over time when it is not reactivated. This means that if a concept is not used or encountered frequently, its strength of activation will decrease over time, making it more difficult to retrieve. Activation will also decrease with each subsequent node that it has to traverse, meaning that the activation between more closely related words will be stronger than between more remotely related ones. One of the strengths of the spreading activation model is its ability to explain a wide range of phenomena and provide a consistent account of semantic priming effects across different tasks and contexts. The incorporation of both lexical and semantic networks also allows the spreading activation models to explain such problematic cases as mediated priming (when two words are not related directly, but are linked through a mediating concept, e.g. *lion – (tiger) – stripes*) or graded priming (when the priming effect is smaller for more distantly related than for more closely related words, e.g. *cucumber – celery* versus *cucumber – pumpkin*, Vigliocco and Vinson 2012). A potential limitation of the spreading activation model is that it is overly general and focuses on automatic processes without accounting for strategic mechanisms that may contribute to priming effects (Hutchison 2003; McNamara 2005; also see Section 1.3.3).

Distributed network models (McClelland and Rumelhart 1985; Masson 1995; Moss et al. 1994; Plaut 1995; Plaut and Booth 2000) also consider the mental lexicon as a network of nodes; however, they borrow from the feature-based theories of semantic memory and propose that the nodes are represented by interconnected features rather than whole concepts (Hutchison 2003). Unlike localist models, in which each node can be conceptually interpreted, distributed models introduce a hidden layer between input (e.g. letters) and output (e.g. semantic features), and nodes of these hidden layers are difficult to interpret (Page 2000). According to this approach, the meaning of a concept is distributed among multiple nodes in the hidden layer and can be characterised by a particular pattern of activity across these nodes. The patterns of activity for related concepts are similar, which explains the facilitatory effect for target words when they are preceded by a related prime. For example, Plaut and Booth (2000) proposed a distributed-network simulation of priming effects in the lexical decision task that incorporated different factors influencing reaction times (e.g. word frequency, SOA, individual differences) into a single mechanism of lexical processing. Their model included a hidden layer with 100 units that were connected to the input layer of 18 orthographic units and to the output layer of 100 semantic units (see Fig. 4). The model was trained with 200,000 word representations and was found to simulate reaction times from three lexical decision experiments with different groups of participants (although see Borowsky and Besner (2006) for the criticism of the single-mechanism account).

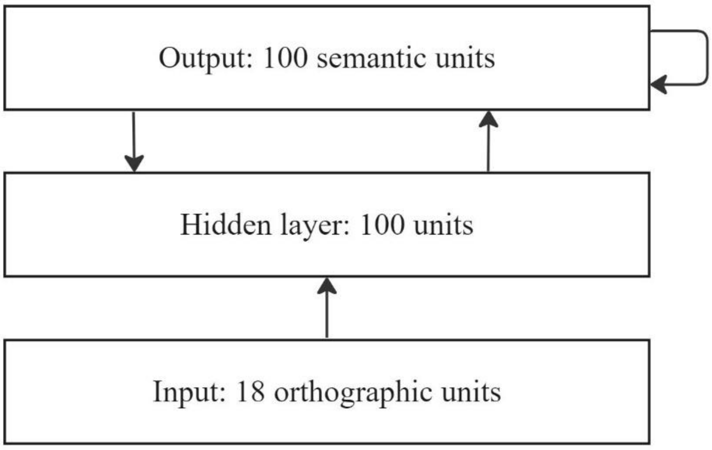

Fig. 4. The architecture of the single-mechanism distributed network (adapted from Plaut and Booth 2000).

An important difference between distributed and localist models is that, under the distributed network account, it is not necessary for the entire concept to become activated for the activation to spread on to neighbouring concepts (Hutchison 2003). Another crucial characteristic of this type of models is that they are dynamic and able to learn new meanings and re-adjust the weights of connections between nodes. Thus, if a particular pattern of activation occurs frequently, for example, as a result of training or specific environment, the connections between respective concepts will become stronger. Vice versa, if a pattern of activation is not repeated over a long period of time, for example, as a result of re-training or forgetting, the strength of connections will slowly decay. Since the pattern of activation may also involve lexical co-occurrences, some distributed models (Masson 1995; Moss et al. 1994; Plaut and Booth 2000) can explain both associative and semantic relationships in the priming paradigm (also see Hutchison 2003). At the same time, distributed models are challenged by empirical findings showing mediated priming (Balota and Lorch 1986; McNamara and Altarriba 1988; Kuperberg et al. 2008) because this type of priming appears to require the activation of a mediating concept in the absence of a shared pattern of activation between, for example, *lion* and *stripes* (Hutchison 2003).

Unlike the spreading activation and distributed network models, compound-cue models of semantic priming (McKoon and Ratcliff 1992; Ratcliff and McKoon 1995) focus on the integration of information from various sources rather than on the spreading activation and the structure of the semantic memory. Compound-cue models propose that semantic priming emerges from the activation of multiple independent sources of information that converge to support word recognition and processing. According to these models, primes and targets form a compound in the short-term memory that serves as a retrieval cue in the long-term memory. Compounds can vary in terms of their familiarity, and in highly familiar compounds targets are recognised faster, which explains the semantic priming effects. For example, a compound for the prime *dog* can include a set of concepts, such as *pet*, *cat*, *bone*, etc., whose composition will depend both on experience and co-occurrence of words in language. The compound-cue account of semantic priming links this phenomenon to broad theories of memory, but it often fails to explain empirical results from linguistic studies (Lucas 2000; Hutchison 2003; McNamara 2005).

The above models suggest that semantic priming is a multi-faceted phenomenon that can be studied from various perspectives. Not only has the semantic priming effect been observed in different kinds of tasks and contexts (Neely 1991; McNamara 2005), but it has also been shown to depend on a range of lexical and semantic factors. For example, there is evidence that the semantic priming effect is larger with longer SOAs (Plaut and Booth 2000), for shorter primes, for high-frequency primes, and for primes with a lower number of orthographic neighbours (Hutchison et al. 2008). Other factors that may impact the priming effect are the direction and strength of associative and semantic relatedness (Hutchison 2003; Radel et al. 2012; Thomas et al. 2012; Ortu et al. 2013), the distinction between which is discussed in more detail in the following section. Furthermore, executive functions, such as attentional control or working memory (Hutchison et al. 2014; Heyman et al. 2015, 2017), can also play an important role in semantic priming and will be reviewed in Section 1.3.3.

1.3.2. Associative versus semantic relations

Associations may be any words or expressions that come to one's mind in response to a stimulus word. They have for a long time been an effective means of examining mental representations of words and their relations (see Section 1.2.2). However, associative relations, which mostly result from the co-occurrence of words in a language (e.g. *spider* – *web*), may differ from semantic relations, which are usually understood in terms of feature overlap (e.g. *dolphin* – *whale*). Whereas many semantic processing studies do not distinguish between these two notions and use them interchangeably, other studies make a distinction between associative and semantic relations (Xavier Alario et al. 2000; Perea and Rosa 2002; Hutchison 2003; Ferrand and New 2004) although their exact interplay is a matter of an ongoing debate. This distinction appears to be particularly relevant for priming studies that usually involve the presentation of two related words. There have been multiple attempts in the literature to isolate associative from semantic priming effects, often resulting in indecisive or even contradicting findings. This section presents an overview of some of these studies and presents a current view on the interaction of semantic versus associative relationships.

Lucas (2000) conducted a meta-analysis of 26 earlier studies to compare semantic and associative priming effects. However, she pointed out that due to different methodologies and stimulus selection criteria, it was difficult to find a single point of reference for selecting purely semantic priming studies. In effect, studies in which "author(s) explicitly stated that some attempt (of any kind) was made to control for associative relationships among prime-target pairs" (Lucas 2000: 620) were considered to investigate semantic but not associative priming. It was found that automatic priming can be observed when primes are semantically but not associatively related to the targets (cf. Thompson-Schill et al. 1998). The presence of an associative relationship between words in addition to the semantic one was reported to add a "boost" in the size of the priming effect. These findings were later reconsidered by Hutchison (2003) who examined different types of associative relations and found evidence of automatic priming also for associatively related pairs that were not semantically related. This effect was the most prominent for mediated associates, i.e. pairs that share little to no semantic features but are related through an associative link, e.g. *lion – (tiger) – stripes*.

Focusing specifically on the distinction between associative and semantic priming, Perea and Rosa (2002) selected Spanish prime-target pairs that were related only semantically or both semantically and associatively. Semantically related words were selected from three categories: synonyms (e.g. *country – NATION*), antonyms (e.g. *war – PEACE*) and category coordinates (e.g. *table – CHAIR*). The measures of associative relatedness were obtained from Spanish free association norms. Four lexical decision experiments were conducted to investigate automatic semantic and associative priming effects. It was hypothesised that if automatic priming was observed only for semantically related pairs, then the facilitation effect should probably arise from spreading activation in the semantic network based on shared features between related concepts. If, on the other hand, automatic priming also occurred for pairs that were both semantically and associatively related, it would suggest that the spreading activation can also take place in the lexical network based on word co-occurrence in language. Their results showed different patterns of the semantic priming effect depending on the timing of stimulus presentation and the interval between stimuli and responses. The authors concluded that both associative and semantic relatedness contributes to the priming effect in a complex way and that no exclusively semantic or exclusively associative priming model was able to account for their results. They also emphasised the importance of carefully selecting stimuli for studies aiming to disentangle semantic and associative relations. The design of Perea and Rosa's (2002) experiments also allowed them to investigate the time course of the facilitation effects. Both associatively and semantically related pairs showed an earlier increase in the priming effect, whereas the effect for only semantically related pairs disappeared faster. It suggested that the spreading of activation in the co-occurrence-based lexical network is faster than in the concept-based semantic network.

Whereas Perea and Rosa (2002) studied prime-target pairs that had only semantic or both semantic and associative links, they did not include pairs that were only associatively related. Trying to explore purely semantic and purely associative priming within the same experiment, Ferrand and New (2004) selected French words that did not overlap in terms of their semantic and associative relatedness. Associative strength was obtained from association norms, whereas the degree of semantic relatedness was judged by participants on a 7-point scale. Associatively and semantically related pairs were then tested with other groups of participants in three lexical decision experiments with different prime durations. The results of their behavioural experiments provided evidence in favour of both semantic priming in the absence of lexical links between primes and targets and associative priming in the absence of semantic links. The above studies focused on word recognition processes, but similar findings were also reported in a primed picture-naming experiment (Xavier Alario et al. 2000) which found that both associative and semantic priming effects occur in speech production.

Although many earlier studies focused on dissociating semantic from associative priming effects and describing their implications for semantic memory theories, the division between purely semantic and purely associative relations remains a matter of debate. The selection of associatively and semantically related stimuli also poses a problem. Semantically related words were mostly selected based on their sharing some features or belonging to certain categories, such as synonyms, antonyms, or members of the same class. However, as McRae et al. pointed out, “meaningful semantic relations between words/concepts certainly extend beyond category coordinates” (2012: 40). In turn, a serious caveat of the feature overlap approach to selecting semantically related words is that such measures often include only concrete nouns (Ortu et al. 2013). At the same time, associatively related words are most frequently selected based on free association norms based on the assumption that free associations reflect the patterns of word co-occurrence in language. However, it has been shown that word associations heavily rely on meaningful semantic relations between cues and responses (McRae et al. 2012; Vivas et al. 2019).

Given that many related words share both associative and semantic features, some distributed models of semantic priming (Masson 1995; Moss et al. 1994; Plaut and Booth 2000) also accounted for potential effects of associative relatedness. For example, in Plaut and Booth’s (2000) computational simulation of semantic priming effects, a provision was made for the probability that categorically related items could also be related associatively. Distributional semantic models, such as HAL, LSA, and, more recently, *word2vec* (see Section 1.2.3 for an overview) also support the departure from the binary division between semantic and associative relations. They provide a different perspective on semantic relatedness going beyond feature overlap or synonymy/antonymy. At the same time, distributional semantic models that involve dimensionality reduction (e.g. LSA) or hidden learning layers (e.g. *word2vec*) are able to account for mediated priming (e.g. *lion – (tiger) – stripes*), which in traditional models used to be explained through associative links. An alternative view aimed to resolve the debate about the long-standing dichotomy is proposed by Kumar (2021), who suggests that semantic and associative relations fall on a continuum ranging from direct links representing local associative co-occurrences to indirect links representing more distant semantic relations.

In the present project, the topic of semantic versus associative relations is of vital importance and will be revisited in two studies. Chapter 3 describes a free word association experiment in Polish, which aimed to compare associatively related words against semantically related words obtained in a previous study (Rataj et al. 2023). Furthermore, it compared the measures of associative strength with the measures of semantic similarity derived from *word2vec* semantic spaces. In turn, Study 3 (Chapter 5) investigated the differences in facilitation effects of related versus unrelated pairs between native and non-native speakers of English depending on the type of word-pair association. It will further critically examine the role of semantic and associative relations in semantic processing in the native and non-native language.

1.3.3. The role of executive functions in semantic priming

Important and long-lasting questions are whether and how semantic priming relies on domain-general processes, such as attention, memory, and executive control. The automatic spreading activation account suggests that semantic priming is unintentional and is not influenced by the allocation of additional cognitive resources to the task (Posner and Snyder 1975). A crucial implication of this account is that, provided semantic activation is automatic, it should also be capacity-free and should not be affected by the imposition of a concurrent task (Neely and Kahan 2001). However, there is convincing evidence that semantic activation is not purely automatic and that the semantic priming effect may depend on executive functions and strategic processes (see McNamara 2005 for a review).

Two main strategic mechanisms have been proposed to contribute to the semantic priming effect. The proactive expectancy generation strategy (Becker 1980; Neely 1991) suggests that, once people see a word, they make a number of predictions regarding what the following word might be. If the next word is among the anticipated candidates, its recognition is facilitated and occurs faster. A second mechanism is referred to as retrospective semantic matching and involves checking the target against previously presented words (e.g. Neely and Keefe 1989; Thomas et al. 2012; Hutchison 2002; Hutchison et al.

2014). Semantic matching is particularly effective in lexical decision tasks where related primes are associated with existing words rather than non-word targets.

Evidence for the involvement of domain-general strategic processes in semantic activation often comes from studies that manipulate one of executive functions and see whether this manipulation has an influence on the performance in priming tasks. For example, Radel et al. (2015) focused on the impact of executive control on semantic processing. They used stimuli with three levels of prime-target relatedness and investigated the effect of inhibition demands on semantic priming in a subsequent semantic priming lexical decision task with a 400 ms SOA. The level of inhibition demands was manipulated in a Simon task with a high or low number of incongruent trials before the semantic priming lexical decision task. It was found that, after participants were exposed to a high-inhibition task and their inhibitory resources were depleted, indirectly related primes resulted in a larger priming effect in the lexical decision task than after a low-inhibition task. The larger priming effect for indirectly related primes under disinhibition conditions suggests that semantic activation can be modulated by control demands.

The relationship between attentional control (AC) and associative priming was investigated by Hutchison et al. (2014). They hypothesised that the proactive expectancy generation strategy may depend on how well participants can focus on potential targets. To distinguish between prospective and retrospective strategies, they used stimuli with different types of prime-target association: forward associates (FA, e.g. *atom – bomb*), backward associates (BA, e.g. *fire – blaze*), and symmetric associates (SYM, e.g. *brother – sister*). Lexical decisions for asymmetric FA and BA pairs were assumed to tap specifically into prospective and retrospective strategies, respectively. The SOA was also manipulated (250 ms and 1,250 ms) to distinguish between automatic and strategic processes involved in semantic priming. Participants' level of attentional control was measured in a battery of tests, including operation span, antisaccade, and Stroop tasks. In line with the researchers' expectations, individuals who performed better on AC tests demonstrated a greater priming effect for FA associates than those with lower AC results. Low-AC individuals, in contrast, demonstrated a higher priming effect for BA pairs in the later quantiles of the reaction time distribution. The pattern of effects did not depend on the SOA. These results support the assumption that people with good cognitive control skills are more likely to employ prospective strategies, whereas low-AC individuals prefer to rely on retrospective processes.

Working memory is another important executive function closely related to language processing. Because working memory has limited capacity (Cowan 1999; Baddeley et al. 2020; also see Chapter 2), it is reasonable to assume that exhausting working memory resources should have an effect on semantic processing. Investigating the impact of working memory load on semantic processing is one of the objectives of the present thesis, so a more detailed theoretical discussion of research into working memory and its relation to language will be presented in Chapter 2. Furthermore, an experimental study exploring the influence of different types of working memory load on semantic relatedness judgements will be described in Chapter 4 (Study 3). Here, several studies will be discussed that specifically focus on the role of working memory in semantic priming and strategic semantic processing. Previously, only few studies have investigated the interaction between working memory and semantic processes. For example, no effect of working memory load on the priming effect was found in experiments involving a lexical decision task with identical primes and targets (Perea et al. 2018). The primes were presented for very briefly (50 ms) following a forward mask (#####). This procedure was supposed to tap into automatic semantic activation mechanisms that do not require conscious attentional resources. The secondary working memory tasks differed in the level of difficulty and included matching of a string of letters or searching for a number in a previously presented series. Regardless of the working memory manipulations, the magnitude of the priming effect did not significantly differ across experiments, which supported the automatic account of masked priming in lexical decision tasks.

The effect of working memory load in a task involving conscious semantic processing of non-identical primes and targets was investigated by Heyman et al. (2015). Their study involved native Dutch speakers who completed a semantic priming lexical decision task after memorizing an easy (low-load condition) or complex (high-load condition) dot pattern. In the lexical decision task, the prime was presented for 150 ms, but the SOA was either 200 ms or 1200 ms. Similar to Hutchison et al.'s (2014) study, the materials included FA, BA, and SYM prime-target pairs. Following the evidence from Hutchison et al. that expectancy generation requires cognitive resources as opposed to semantic matching, it was expected that a more complicated version of the dot memory task would tax executive resources required for prospective but not for retrospective cognitive processes. As a consequence, in the high memory load condition, priming for FA pairs would be reduced, whereas priming for BA and SYM pairs would not be affected.

The results fully confirmed the hypothesis: the Load x Type of Association x Relatedness interaction was found to be significant because the priming effect was almost eliminated for FA pairs in the high-load condition as compared with the low-load condition, whereas the priming effect was the same for BA and SYM pairs. There was no interaction between these factors and SOA. These findings challenge the fully automatic spreading activation accounts of semantic priming and support Hutchison et al.'s (2014) assumption that prospective priming, which is based on expectancy generation, relies on working memory capacity. However, the exact mechanism of the interaction between prospective semantic priming and working memory remains unclear.

In an attempt to replicate Heyman et al.'s (2015) results, Heyman et al. (2017) conducted two further semantic priming lexical decision experiments, in which working memory load was manipulated. Both experiments had the same design and procedure as the original study. The main differences of the first experiment were that it was carried out in a different language (English instead of Dutch) and in a different testing environment. The second experiment in turn was a very precise replication of the original study with the only major difference being a larger sample of participants (almost twice as many).

Despite the similarities, Heyman et al. (2017) failed to replicate Heyman et al.'s (2015) crucial results that pointed to the dependency of forward priming on working memory load. Although the researchers observed the expected main effect of load, relatedness and the type of association, the Load x Type of Association x Relatedness interaction was not significant. As acknowledged by the authors, a possible reason for this discrepancy in results may be the non-verbal nature of the dot memory task used to manipulate working memory load in both studies. Another explanation may be that the non-verbal task was not demanding enough to cause any significant differences in how participants performed in the lexical decision task. Whereas previous research focused on the role of different executive functions in semantic priming, there have been no studies that have investigated the differential effect of spatial and verbal working memory on semantic processing. This research gap is filled by the experiment presented in Chapter 4, which explored the influence of working memory load in different domains on semantic relatedness judgements.

1.3.4. Semantic priming in the native and non-native language

According to Eurostat, 65% of working-age adults in the European Union knew at least one foreign language in 2016 (Eurostat 2018) and almost half of upper secondary pupils were learning two or more foreign languages in 2020 (Eurostat 2022). On the global scale, it is estimated that most of the world's population use two or more languages (Grosjean 2021) on an everyday basis. It means that the majority of people have been to some degree exposed to a non-native language in their life. This inevitably raises a question about cognitive implications of having to handle more than one language and about the organisation of the mental lexicon in a non-native language.

The semantic priming paradigm remains an effective method of investigating semantic processing in multilinguals. In fact, it becomes even more attractive because, in addition to different types of prime-target relatedness, the bilingual aspect adds another dimension to research questions and stimuli. Primes and targets can be presented in different combinations of participant's first (L1), second (L2) or other (Ln) language; moreover, they can also include words that have similar form and meaning (cognates) or similar form and different meaning (interlingual homographs and interlingual homophones, or false friends) in two or more languages. Difficulties, however, arise with designing multilingual experiments and interpreting their results because of multiple confounding variables, such as the level of proficiency in a non-native language, the age and context of foreign language acquisition, characteristics of languages in question, and many others.

The semantic priming effect in native and non-native speakers was for the first time compared by Frenck-Mestre and Prince (1997) in a lexical decision task with different categories of prime-target pairs (antonyms, synonyms, and collocations). Participants in one of their experiments included three groups of English speakers: native speakers, proficient bilinguals, and non-proficient learners. To prevent participants from engaging in strategic processing, the procedure involved forward prime masking and a very short (67 ms) presentation of the prime. The semantic priming effect was observed in all three groups for all types of prime-target pairs, with a lower magnitude for non-proficient learners and a comparable magnitude for proficient non-native and native speakers. It was also found that the facilitation effect for non-dominant meanings of foreign words persists only in proficient bilinguals, and not in intermediate learners. These findings suggest that automatic spreading activation can effectively occur in a non-native language and depend on the level of non-native speakers' proficiency. More generally, the results indicate relative autonomy of the non-native mental lexicon and similarities in the semantic memory structure in the native and non-native language.

A similar pattern of results in terms of semantic priming in a non-native language was obtained by Phillips et al. (2004) in a study that combined behavioural and electrophysiological evidence. In their experiments, English native speakers with a different level of proficiency in the non-native French language performed a lexical decision task in either English (L1) or French (L2). The results revealed a significant semantic priming effect in both language conditions and suggested greater automaticity in L1 than in L2 and in more proficient than in less proficient bilinguals, as evidenced by the measure of intra-individual variability. These findings were highly consistent in the analyses of both reaction times and event-related potentials, indicating that the efficiency of automatic processing in a non-native language can be measured by patterns of electrical brain activity, as well as the timing of behavioural responses.

Another study involving native and non-native speakers of English (Ankerstein 2014) provided additional support to the accounts of automatic semantic priming in a non-native language. Although non-native speakers were overall significantly slower at deciding whether or not the presented target was an existing English word, the semantic priming effect was qualitatively and quantitatively very similar across two groups in terms of both accuracy and speed. Additionally, the authors reported a stronger priming effect for high-frequency than for low-frequency words in both language groups.

An important question with regard to bilingual language processing is whether the native language also gets activated during non-native language comprehension. General models of bilingual processing that include semantic representations, such as BIA+ (Dijkstra and van Heuven 2002; Van Kesteren et al. 2012) and Multilink (Dijkstra et al. 2019), view the bilingual mental lexicon as a shared pool that is language non-specific. It implies that when bilinguals encounter words in any language familiar to them, an integrated semantic system becomes activated. These models suggest similar semantic activation mechanisms in the native and non-native language, but they do not directly account for facilitation effects of related versus unrelated words in different languages. There is mounting evidence from several studies that speakers can indeed unconsciously access native-language (L1) semantic representations when operating in their non-native language (L2). For example, in a carefully designed electrophysiological study Thierry and

Wu (2007) demonstrated that the pattern of brain activity registered during relatedness judgements of semantically related or unrelated L2 English word pairs suggested activation of participants' L1 Chinese without participants being aware of this. Their stimuli included English words, for half of which the Chinese translations had one character in common. Whereas there was no effect of Chinese character repetition on reaction times, the reduced amplitude of the N400 component in pairs that shared a Chinese character revealed that participants unconsciously accessed L1 translations of words that they were processing in their L2. The N400 component is a negative-going pattern of event-related brain potential responses that peaks around 400 ms after the presentation of semantically anomalous stimuli. It is often viewed as a neurophysiological correlate of semantic relations (Kutas and Hillyard 1980; Kutas and Federmeier 2011). Thierry and Wu's (2007) findings in the visual modality were also replicated in the auditory modality. A follow-up study with a similar design (Wu and Thierry 2010) demonstrated that it is the sound and not the spelling of L1 translations that is activated during L2 comprehension.

Further evidence in favour of automatic activation of L1 Chinese translations in L2 English tasks comes from Zhang et al. (2011). They conducted two experiments involving a masked priming lexical decision task with primes that included English translations of the first or second morpheme of compound Chinese words, whose English translations served as targets. It was found that only covert first-morpheme translations facilitated the recognition of target words, which suggests automatic activation of non-native language and morphological decomposition of L2 translations. The findings of this hidden repetition priming were however not replicated by Wen and van Heuven (2018), who instead provided evidence that the automatic translation is limited to target words but not primes. Another study supporting language-nonselective activation in bilingual processing (Morford et al. 2011) demonstrated that L1 translations during L2 comprehension can be accessed not only across different scripts, but also across different modalities. Thus, native users of American Sign Language were shown to activate sign translations when performing a semantic relatedness task in their L2 English.

Studies investigating semantic processing within a non-native language yield interesting results, but they are quite limited in number. Much more common are bilingual experiments that involve translation priming or cross-language semantic priming. In translation priming, the target word is a translation equivalent of the prime word, whereas in cross-language priming targets and primes are words that differ in their semantic relatedness and that are presented in two different languages. Priming effects have been found in both priming paradigms, with translation priming generally producing more consistent results than cross-language priming and with L1 primes producing more facilitation for L2 targets than vice versa (Altarriba and Basnight-Brown 2009).

To assess the effect sizes of different masked translation priming studies, Wen and van Heuven (2017) conducted a meta-analysis of published articles on the topic. They found evidence that for masked translation priming, target recognition is facilitated in both L1-L2 and L2-L1 priming direction with the former producing significantly larger priming effects. These findings support the idea that L1 and L2 share the same lexico-semantic structures, but L1 primes are able to activate a larger number of semantic nodes shared between two languages than L2 primes (Schoonbaert et al. 2009; Smith et al. 2019).

Cross-language semantic priming has also been tested across different modalities (Tytus and Rundblad 2016) and in languages from distant language families (Keatley et al. 1994). Although the findings in the literature for L2-L1 priming direction did not always reach significance levels, the priming effect was found more consistently in the L1-L2 direction. An overview of studies using cross-language priming paradigm is presented in Table 1.

Table 1. An overview of cross-language semantic priming lexical decision studies.

Authors	Languages	Summary
de Groot and Nas 1991	Dutch (L1) – English (L2)	No significant cross-language semantic priming effects from L1 to L2.
Keatley et al. 1994	Chinese (L1) – English (L2) Dutch (L1) – French (L2)	Semantic priming effect observed in the L1–L2, but not in the L2–L1 direction in both language pairs.
Duyck 2005	Dutch (L1) – English (L2)	L2 targets are primed by L1 pseudohomophones of semantically related words, but not in the reverse direction.
Basnight-Brown and Altarriba 2007	Spanish (L1) – English (L2)	Significant semantic priming effect in the L2–L1 direction only, which disappeared in the masked condition.
Perea et al. 2008	Basque (L1) – Spanish (L2) Spanish (L1) – Basque (L2)	Equivalent cross-language semantic priming effect for both directions in balanced Basque–Spanish and Spanish–Basque bilinguals.
Schoonbaert et al. 2009	Dutch (L1) – English (L2)	Significant priming effect in both directions (stronger for L1–L2) in the masked lexical decision task.

Smith et al. 2019	Hebrew (L1) – English (L2)	Priming effect only for L1–L2 cross-language semantic priming.

In summary, the majority of studies that have examined semantic priming in a non-native language have focused on cross-language processing. However, the question of whether there are any differences in semantic processing with words in the native versus non-native language remains underresearched. Furthermore, as far as I am aware, no studies have so far investigated the role of strategic mechanisms in semantic processing with words in the non-native language. Study 3 of the present project (Chapter 5) fills this research gap by investigating whether semantic relatedness judgements differ in the native and non-native language and whether they depend on the type of association between words.

1.4. Semantic relatedness task

As discussed in the previous sections, the facilitation effect of related compared to unrelated words has been consistently observed in different settings and tasks. This section discusses the semantic relatedness task, which will be used in Studies 2 and 3 and which is one of the methods for investigating semantic representations and the influence of different factors on semantic processing.

A common method to study semantic representations is the semantic priming lexical decision task, in which participants decide whether a string of letters is an existing word (e.g. *table*) or a pseudoword (e.g. *thrade*) (e.g. Neely 1976; Hutchison et al. 2013). However, another task that has been used to investigate semantic processing is the semantic relatedness task (also called relatedness judgement task), in which participants decide whether pairs of words are semantically related (e.g. *dog – cat*) or not (e.g. *dog – table*) (Balota and Paul 1996; Faust and Lavidor 2003; Kuperberg et al. 2008; Ortu et al. 2013; Gilbert et al. 2018). Because the lexical decision task does not explicitly require participants to access the meaning of words, it is more suitable for investigating automatic semantic processing. At the same time, one of the advantages of the semantic relatedness task is that it more closely resembles natural language processing because participants need to explicitly access the meaning of both words in a pair to perform the task in contrast to the lexical decision task, in which the processing may be limited to form representations (Balota and Paul 1996; Poort and Rodd 2019). Furthermore, the need to access semantic information throughout the task makes relatedness judgements less sensitive to variable task demands and other stimuli involved in the task, when participants could be switching between lexical and semantic processing (Poort and Rodd 2019).

The importance of accessing semantic information for processing targets preceded by multiple primes was demonstrated in a series of experiments by Balota and Paul (1996). They used lexical decision, naming, and semantic relatedness tasks with word triplets in which two primes were either related both to the target and to each other (e.g. *lion – stripes – tiger*) or were related to the target, but not to each other (e.g. *kidney – piano – organ*). Unrelated primes were used in one or both positions as control conditions. Their findings showed that the facilitation effects from two divergent primes did not sum up only for the semantic relatedness task in contrast to the lexical decision task, which suggests that relatedness judgements are particularly affected by the differences between lexical and semantic processing.

Additionally, neuroimaging data presented in Kuperberg et al. (2008) revealed that the semantic relatedness task and the lexical decision task differ in terms of the brain areas recruited during the tasks. Furthermore, the comparison of the reaction time data of the two tasks with directly and indirectly semantically related pairs revealed a larger priming effect for directly related pairs in the semantic relatedness task than in lexical decision task. They also found a reverse priming effect, i.e. slower reaction times for indirectly related versus unrelated pairs in the semantic relatedness task, but no effect in the lexical decision task (see Fig. 5). These results suggest that semantic priming may be modulated by both task and the type of relatedness.

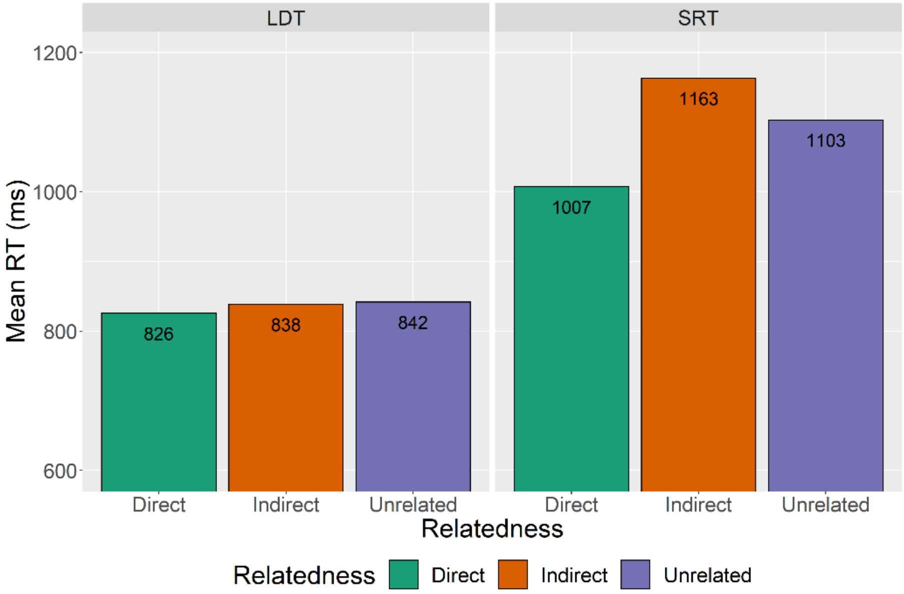

Fig. 5. Mean reaction times as a function of word-pair relatedness in the lexical decision task (LDT) and semantic relatedness task (SRT) in Kuperberg et al. (2008).

The degree of associative relatedness was also shown to affect semantic processing in the semantic relatedness task. Ortu et al. (2013) used highly (e.g. *cherry – tree*) and moderately (e.g. *camera – lens*) associated pairs controlled for semantic relatedness using semantic spaces and found a graded effect of associative strength, with the largest facilitation effect in highly associated pairs and a smaller effect in moderately associated pairs as compared to unrelated pairs. It was also shown that associative rather than semantic relationships modulated meaning processing reflected by the N400 effect.

It can be concluded from Kuperberg et al. (2008) and Ortu et al. (2013) that a different pattern of facilitation effects for indirectly related and moderately associated pairs in the semantic relatedness task demonstrates that the intermediate relatedness condition may be particularly sensitive to task demands. This is consistent with Radel et al.'s (2015) who showed in a semantic priming lexical decision study that indirectly related pairs were sensitive to the manipulation of inhibition demands.

In the present project, the semantic relatedness task will be used to investigate how semantic processing of words with different types of relatedness is impacted by additional working memory load in the verbal and spatial domain (Study 2, Chapter 4) and by the native/non-native status of the language of stimuli (Study 3, Chapter 5). Because relatedness judgements require participants to process and make explicit decisions about the meaning of both words in a pair, this task may be more suitable for the purposes of these studies and is likely to capture the effects of experimental manipulations. Furthermore, the results found in the semantic relatedness task will be compared with similar studies that used a semantic priming lexical decision task.

1.5. Conclusions

The questions of meaning representation and processing have been in the spotlight of psycholinguistic research for the last several decades. This chapter started with presenting the evolution of the theories of semantic memory from early feature-based (Smith et al. 1974; Tversky 1977) and network-based (Collins and Quillian 1969; Collins and Loftus 1975) accounts to elaborate computational (Landauer and Dumais 1997; Landauer et al. 1998; Mikolov et al. 2013) models. Furthermore, influential models of semantic priming were also introduced. Semantic priming refers to a well-established effect of facilitated recognition of words that are preceded by semantically or associatively related relative to unrelated primes.

The distinction between associative and semantic relations between concepts was discussed in detail because it will be important for all experimental studies in the thesis, but in particular for Study 1 (Chapter 3), which investigated whether semantically related pairs from a Polish dataset are also associatively related. Although several studies (see Hutchison 2003; Lucas 2000 for review) tried to isolate these two types of relationships, a more recent approach holds that these are two different, yet often overlapping elements of a relatedness continuum (Vivas et al. 2019; Kumar 2021).

There is also much debate about the dependency of semantic priming on executive functions. Whereas the first theories (Posner and Snyder 1975) suggested that the activation of nodes is automatic and does not require any additional resources, it has more recently been found (Hutchison et al. 2014; Radel et al. 2015) that the activation in the semantic network may depend on other cognitive functions, in particular working memory (Heyman et al. 2015). In this thesis, the effect of different types of working memory load on semantic processing was experimentally tested in Study 2 (Chapter 4).

Furthermore, this chapter discussed the role of native/non-native language status in semantic processing. Although the activation of semantic representations through words in a non-native language depends, among others, on proficiency and may differ from activation through words in the native language, a semantic priming effect was found with words presented in a non-native language (Frenck-Mestre and Prince 1997; Phillips et al. 2004; Ankerstein 2014), in different languages (see Altarriba and Basnight-Brown 2009), or with translated primes or targets (see Wen and van Heuven 2017). There is also some evidence that using a second language may involve native-language semantic representations (Thierry and Wu 2007; Zhang et al. 2011). It is unclear however whether semantic relations are processed differently with words presented in the native and non-native language – a question addressed in Study 3 (Chapter 5).

One of the ways to explore the influence of different factors on semantic processing is to ask participants to judge the relatedness of word pairs while manipulating other variables, such as working memory load or the degree of relatedness between words. This chapter presented several studies that used the semantic relatedness task to investigate semantic processing (Balota and Paul 1996; Kuperberg et al. 2008; Ortu et al. 2013). The semantic relatedness task differs from the commonly used semantic priming lexical decision task in that the former requires deeper semantic processing and is more natural. Moreover, memory demands inherent in the task are likely to make it more sensitive to additional working memory manipulations. A detailed discussion of working memory and its role in language processing will be discussed in the following chapter because it will be relevant for Study 2 (Chapter 4) investigating the impact of different types of working memory load on semantic relatedness judgements.

Chapter 2: Working memory

2.1. Introduction

Working memory is one of the executive functions, i.e. mental processes that are necessary for directing and monitoring our behaviour. Research on working memory started more than half a century ago and has been expanding exponentially ever since (Baddeley 2012; Wen 2019). Although working memory is integral to many aspects of our everyday life (Diamond 2013), its relation to language processing will be of particular significance for this thesis.

This chapter begins with discussing the role of working memory and positioning it among other executive functions. Over the last decades, several theoretical accounts of this phenomenon have been elaborated, the most influential of which are reviewed here. Since the experimental study described in Chapter 4 will focus on the influence of working memory on semantic processing, it is important to understand the relation between working memory and language, which is discussed in the chapter. Finally, this chapter summarises relevant studies that focus on differences between spatial and verbal working memory as this distinction will be crucial for Study 2 (Chapter 4).

2.2. Working memory as an executive function

Executive functions are defined as a set of high-level cognitive processes that allow individuals to engage in goal-oriented behaviour (Diamond 2013; Friedman and Miyake 2017). Executive functions require cognitive effort and contribute to other complex cognitive abilities such as reasoning and planning (Diamond 2013). In the literature, it is common to distinguish between three core executive functions that are responsible for the shifting of mental sets (generally known as cognitive flexibility), updating and monitoring of working memory representations (working memory), and inhibition of prepotent responses (inhibition, or inhibitory control) (Miyake et al. 2000; Diamond 2013; Friedman and Miyake 2017; Amunts et al. 2020; Ober et al. 2020; Glisky et al. 2021).

Over the last decades, there has been much debate about the unity and diversity of executive functions, i.e. whether they are separate cognitive phenomena or represent different aspects of the same underlying ability (Miyake et al. 2000; Friedman and Miyake 2017; Karr et al. 2018; Glisky et al. 2021). On the one hand, all executive functions appear to have shared neural correlates in the frontal lobe (Friedman and Miyake 2017; Glisky et al. 2021) and show functional overlap in studies involving various healthy and clinical populations (for reviews, see Friedman and Miyake 2017; Karr et al. 2018; Amunts et al. 2020). On the other hand, there is some evidence for the separability of executive functions and correlational dissociation between different sub-domains (Miyake et al. 2000; Friedman and Miyake 2017; Glisky et al. 2021). For example, in Miyake et al. (2000) 137 participants completed a series of nine tasks that were supposed to separately test shifting, updating and inhibition abilities, and another five tasks that tested complex executive abilities. The participants' results were then evaluated in a confirmatory factor analysis, which showed that, although moderately correlated, the three executive functions could be clearly separated and contributed differentially to the performance on complex cognitive tasks. Later analyses that factored in age (Karr et al. 2018) and individual differences (Friedman and Miyake 2017) confirmed the dual nature of executive functions. These studies also suggest that distinctions between core executive functions are important when choosing or designing tasks that are expected to tap one function.

Among other executive functions, working memory is especially relevant for the present thesis because Study 2 (Chapter 4) will investigate the influence of working memory load on semantic processing. Working memory involves holding and manipulating information in mind, and it is crucial for our ability to make connections between objects and ideas, to reason about the surrounding reality, as well as to process and comprehend language (Shah and Miyake 1996; Diamond 2013). Working memory plays an important role both in language learning and in general language processing (Gathercole 2007) because we constantly need to draw on our stored knowledge of concepts and different elements of meaning and hold them in memory while processing the incoming linguistic input. Furthermore, working memory is crucial for integrating and organising semantic information. For instance, it is used for holding the meanings of individual words in mind while constructing larger units of meaning, such as phrases and sentences (Horne et al. 2022).

It is important to distinguish between working memory, short-term memory, and long-term memory. Long-term memory refers to the unlimited store of knowledge about prior events and experiences that is preserved for long periods of time and can be accessed consciously or unconsciously (Cowan 2008; Baddeley et al. 2020). In contrast, short-term memory is responsible for holding a limited amount of immediately available information for a short period of time. Working memory is similar to short-term memory in that it has limited capacity and stores information for a short period of time, but it differs from short-term memory because it involves both storing and manipulating information that is not perceptually available (Engle and Kane 2003; Diamond 2013). These two processes were shown to rely on different neural circuits (see Miyake et al. 2000; Diamond 2013) and have different mechanisms because working memory is more closely linked to controlled attention and high-level executive processes (Engle and Kane 2003; Kane et al. 2007). Furthermore, it is working memory rather than short-term memory that correlates with language comprehension abilities (Daneman and Carpenter 1980).

Although working memory is distinguishable from other executive functions, it is not entirely independent from them. Thus, Diamond states that "[working memory] and inhibitory control support one another and rarely, if ever, is one needed but not the other" (2013: 143). Indeed, the ability to focus on relevant items and suppress irrelevant ones is crucial for maintaining goal-related information. Apart from inhibitory control (Engle and Kane 2003), working memory has also been linked to other cognitive functions such as attentional control (Adams et al. 2018; Cowan et al. 2020), long-term memory (Adams et al. 2018) and general fluid intelligence (Kane et al. 2007). Several attempts have been made to incorporate different aspects of the multifaceted phenomenon of working memory into comprehensive models that are discussed in more detail below.

2.3. Models of working memory

Research on working memory came into the spotlight of psychological science after the publication of the seminal work by Alan Baddeley and Graham Hitch (1974) who proposed the first multicomponent working memory model. As an increasing number of working memory studies have been conducted and new empirical data has been accumulated over time, Baddeley and Hitch's model has evolved (Baddeley 2000, 2011, 2021; Baddeley et al. 2020) and several new models have been developed aiming to explain the mechanisms of working memory and its relation to other cognitive functions. The following subsections describe some of the most prominent models of working memory that, taken together, ensure better understanding of this complex phenomenon.

2.3.1. The multicomponent model

The original version of the multicomponent model was developed by Baddeley and Hitch (1974) based on research of short- and long-term memory and two-component memory tasks which involved the use of both memory types. By having participants perform different variations of recall, reasoning and comprehension tasks, the authors concluded that the static short-term memory system cannot explain the entire complexity of their findings and instead proposed a new dynamic working memory system comprising of several distinct elements. According to Baddeley and colleagues, working memory is defined as "a limited capacity system for the temporary maintenance and processing of information in the support of cognition and action" (2020: 10). In their initial model, working memory was subdivided into three components: the phonological loop, the visuospatial sketchpad, and the central executive, as shown in Fig. 6.

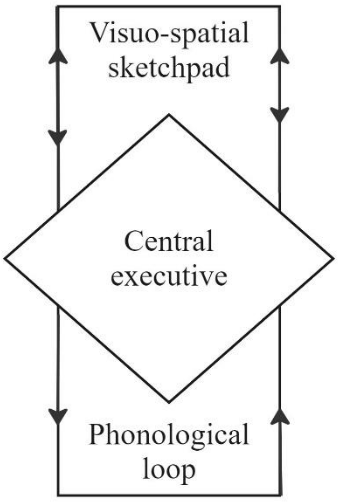

Fig. 6. The original Baddeley and Hitch (1974) working memory model (adapted from Baddeley 2012).

The phonological loop is a limited-capacity store that is necessary for holding verbal information and maintaining it by way of rehearsal. When spoken or written material is presented, it enters the phonological store where it will decay after a short period of time. Repeating the remembered items through the articulatory rehearsal mechanism helps retain the information in the loop until it becomes displaced due to overwriting or interference. Support for the existence of the phonological loop comes from the observation of several phenomena. For example, when people are asked to remember and recall a list of items with similar sounds, e.g. letters B, C, D, their performance tends to be poorer compared to when the items have dissimilar sounds, e.g. letters J, K, N (Conrad and Hull 1964). This so-called phonological similarity effect can be explained by the interference of similar sounds in the phonological loop that is responsible for the storage and rehearsal of verbal information. Similarly, when people are asked to recall sequences of words, their performance deteriorates as a function of word length and articulation duration (Baddeley et al. 1975), suggesting that longer words take more time and resources to rehearse in the phonological loop, potentially leading to less efficient encoding and poorer recall compared to shorter words (Baddeley 2012; Baddeley et al. 2020).

The visuospatial sketchpad is a counterpart of the phonological loop that deals with visual and spatial information. Evidence for the separation of verbal and visuospatial components comes from dual-task experiments, in which participants simultaneously perform tasks that engage a specific working memory domain (Baddeley et al. 1973). Baddeley and Hitch (1974) demonstrated that interference occurred only when both tasks involved the same domain, suggesting that verbal and visuospatial information is processed separately. This finding has important implications for this thesis because Study 2 presented in Chapter 4 focuses on differential effects of verbal and spatial working memory on semantic processing.

The central executive is viewed as a control interface between the other components and performs several important functions. It is responsible for guiding attention to goal-relevant information and dividing attention between different streams of stimuli; it supports decision-making and strategic thinking; and it facilitates switching between different tasks (Baddeley et al. 2011; Baddeley et al. 2020).

The original model comprised three components, but a fourth system named the episodic buffer was added to the model in 2000 (Baddeley 2000). The main function of the episodic buffer is to serve as an interface between other working memory components, perceptual input and long-term memory. This temporary buffer store allows information from different sources to be integrated into chunks, or episodes, that are required for conscious awareness (Baddeley 2000, 2012; Baddeley et al. 2011).

The multicomponent model is constantly evolving and incorporating new empirical evidence. The current version of the model (Baddeley et al. 2020) is illustrated in Fig. 7. In addition to the components described above, it includes various sources of perceptual information that is fed to and registered by individual components. Each of the components is assumed to have limited capacity that can be temporarily enhanced through other high-order executive processes, such as selective attention.

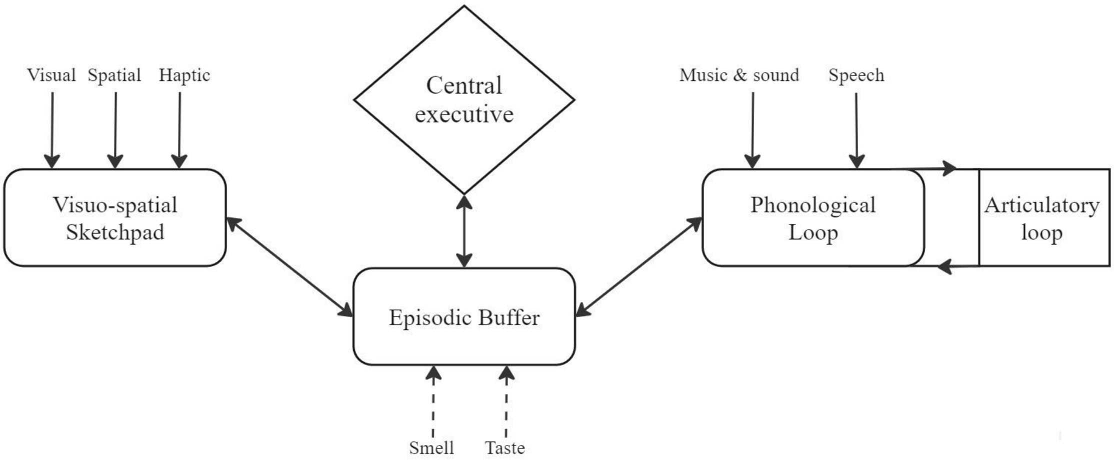

Fig. 7. A revised multicomponent working memory model (adapted from Baddeley et al. 2020).

As the authors themselves admit (Baddeley 2012; Baddeley et al. 2020), the model was not designed as an exhaustive and rigid system, but rather as a general framework that allows mapping new knowledge as it appears. The advantage of the multicomponent working memory model is that it has been effective and flexible enough to successfully incorporate new findings in the field for almost five decades now. However, there remain questions that this model struggles to address, such as the exact role of attention and individual differences (Adams et al. 2018), so alternative approaches to representing working memory have been put forward.

2.3.2. The embedded-processes model

Cowan (1988) initially proposed a general information processing model that included a memory component, which later came to be known as the embedded-processes model of working memory (Cowan 1999). It is similar to Baddeley and Hitch's (1974) model in that working memory is viewed as a limited-capacity system dependent both on sensory input and executive processes. However, its main focus is on the interaction between attention, long-term memory and working memory.

According to Cowan's umbrella definition, working memory is "the ensemble of components of the mind that hold a limited amount of information temporarily in a heightened state of availability for use in ongoing information processing" (Cowan et al. 2020: 45). In this model, schematically illustrated in Fig. 8, information about external stimuli enters through a brief sensory store and activates a domain in the long-term memory based on the features of the stimuli. Unlike the multicomponent model of Baddeley and colleagues (Baddeley and Hitch 1974; Baddeley 2000, 2011; Baddeley et al. 2020), the embedded-processes framework makes no distinction between different sources of information and views submodules of the long-term memory as feature-based and interrelated, suggesting that one and the same stimulus may activate the representations of phonology, colour, orthography, shape, etc. or any combination of them. Because different stimuli may have features that overlap and interfere with one another, the activated features will be constantly updated and replaced.

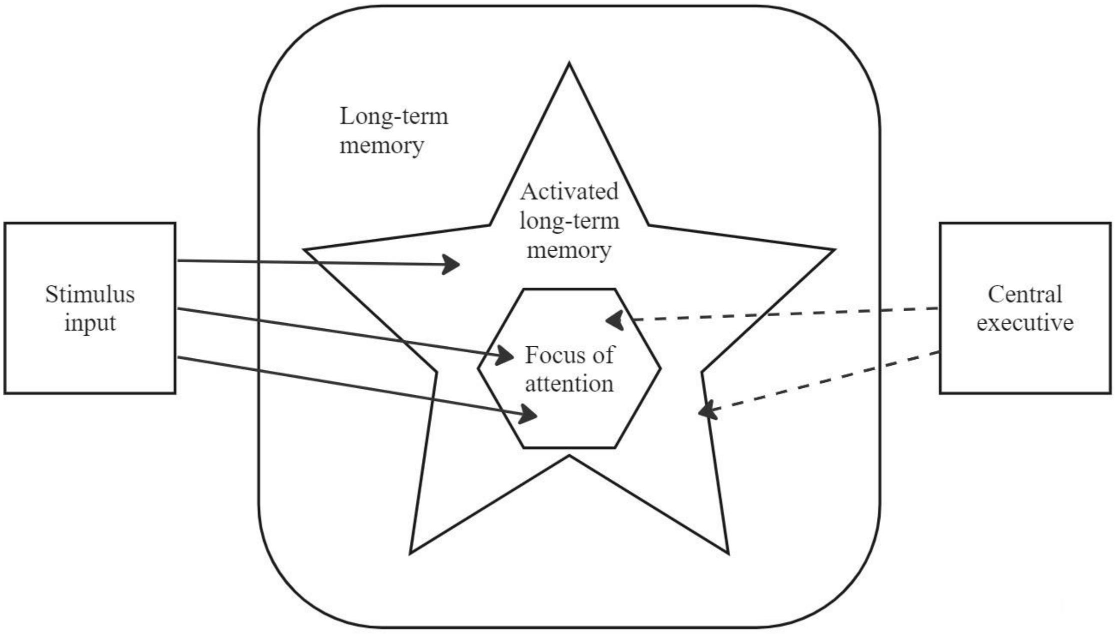

Fig. 8. Embedded-processes model (adapted from Cowan et al. 2020).

A crucial element of the model is the focus on attention, which refers to the part of the activated portion of the long-term memory that is currently attended to. The amount of information that can be in the focus of attention at any given time is limited to a few individual items. Cowan (2010) notes that the number of meaningful chunks that a healthy young adult can simultaneously keep in the central component of the working memory varies from 3 to 5 depending on task conditions and individual differences. Activated features of new and recently attended items can be linked together and contribute to the neural model of the environment. A change in the neural model will shift the attention, and this change can occur either under the influence of salient external stimuli, such as an abrupt sound, or through central executive processes that allow goal-directed attentional control. Thus, attentional and executive processes, retrieval from long-term memory, and memory activation are the mechanisms that work together within the model to ensure functioning of the working memory system.

Like Baddeley and Hitch’s (1974) multicomponent model, Cowan’s embedded-processes model is a broad framework that is not expected to elaborate on every detail of the working memory system or predict specific experimental outcomes. A strength of this model is that it is able to support a large body of research using various methodologies, including behavioural, electrophysiological and neurophysiological techniques (Cowan et al. 2020). Furthermore, it takes into account voluntary and involuntary processes that govern attentional mechanisms and provides insight into the role of attention and working memory capacity in information processing.

2.3.3. Alternative accounts of working memory

The advantage of Baddeley and Hitch’s multicomponent model (Baddeley and Hitch 1974; Baddeley 2000; Baddeley et al. 2020) and Cowan’s embedded-processes model (Cowan 1988, 2010; Cowan et al. 2020) of working memory is that they provide relatively simple and schematic frameworks that can explain many mechanisms involved in behaviours and tasks requiring working memory. However, a growing number of studies dealing with different aspects of working memory have given rise to alternative views on particular aspects of this executive function and its interaction with other cognitive abilities.

Most of the models of working memory agree on the importance of executive attention for working memory. Executive attention, also sometimes called selective attention, refers to the ability to ignore irrelevant stimuli and attend to relevant stimuli depending on the circumstances (Diamond 2013). With regard to working memory, for instance, Barrouillet and Camos (2007, 2020) emphasize in their time-based resource-sharing model that both processing and storage of task-relevant information are reliant on the same limited-capacity attentional resource. Attended items become activated in working memory, but the activation is subject to decay once attention is directed away from the item. To prolong the time of activation, the focus of attention should constantly be switched back and forth between processing new items and maintaining previous ones. Because these processes share common resources, only one process can be performed at a time due to the so-called central executive bottleneck. According to Barrouillet and Camos’ time-based resource-sharing model, successful performance on tasks requiring working memory depends on the allocation of shared resources, attention switching and the time course of these processes.

The idea of shared limited-capacity resources and the distinction between the maintenance and processing functions of working memory is central for studies investigating individual differences in working memory capacity and other cognitive abilities. Daneman and Carpenter (1980) were the first to show that performance on complex span tests that engaged both storage and processing components of working memory strongly correlated with various reading comprehension measures, such as accuracy in answering factual and pronoun reference questions after reading narrative passages. For the purposes of their study, they designed a reading span test, in which participants had to read sets of sentences (processing component) as well as remember and later recall the last word in each of the sentence from the set (storage component). The number of sentences in the sets increased from two to six, and the working memory score was assumed to be the level at which participants correctly recalled words in two out of three sets with the same number of sentences. This measure combining two different aspects of working memory was shown to be a more precise predictor of reading comprehension scores than simple span tests, in which participants did not read sentences and only had to recall single items in the direct or reverse order. A variety of other complex span tests have subsequently been developed to test spatial and verbal working memory capacity (Engle et al. 1999; Kane et al. 2004; Conway et al. 2005); at the same time, the original reading span test was improved, standardized and translated into languages other than English (van den Noort et al. 2008; Biedroń and Szczepaniak 2012).

Not only are complex span tasks recognized to be a reliable measure of working memory capacity, but they were also shown to be strong predictors of other high-order cognitive capabilities (Engle 2002; Kane et al. 2004). Engle et al. (2002) even suggested that, rather than indicating the extent of individuals' memory per se, working memory capacity reflects individuals' ability to control attention for maintaining goal-relevant and suppressing goal-irrelevant information. Regardless of the mechanisms involved, working memory capacity has been found to be related to general intelligence and reasoning (Engle et al. 1999; Engle 2002; Kane et al. 2004; Harrison et al. 2015; Burgoyne et al. 2021), visual attention, i.e. the ability to attend to specific locations or objects (Shipstead et al. 2012; Bleckley et al. 2015), and selective attention (Colflesh and Conway 2007; Poole and Kane 2009).

In addition to the models described above, there are also other attempts to elucidate the functioning of working memory either by extending and elaborating on the existing theories (e.g. the multicomponent working memory model with distributed executive control by Vandierendonck (2020)) or by using neuroscience methods (Postle 2020) and computational approaches (Oberauer 2020). An in-depth overview of the existing working memory models is provided in the edited volume by Logie et al. (2020b), in which authors of different models answer specific questions from the editors, thus clarifying their views and discussing potential limitations. Another perspective on summarising working memory theories is proposed by Adams et el. (2018), who focused on three criteria, or continua, to distinguish between different models in the literature: modularity, attention focus, and purpose. With the multitude of recent studies in the field of working memory research, it is clear that new accounts of working memory will continue to develop. However, as pointed out by Logie et al. (2020a), the different theories and approaches do not necessarily conflict, but rather aim to complement each other and answer different research questions.

2.4. The relationship between working memory and language processing

The ability to temporarily hold and mentally manipulate limited amounts of information is critical for learning and using a language. Therefore, linguistic tasks and measures have been highly instrumental in advancing theories of working memory. Indeed, since the very first years, research on working memory has been inseparable from language research (Baddeley and Hitch 1974; Gathercole and Baddeley 1993; Baddeley 2003, 2011; Adams et al. 2018; Chai et al. 2018; Wen 2019; Schwieter and Wen 2022b). For example, Baddeley and Hitch (1974) made extensive use of various verbal tasks to develop their first version of the multicomponent working memory model, whereas Daneman and Carpenter (1980) were among the first ones to demonstrate the relationship between individual differences in working memory capacity and performance on language tasks. The significance of working memory has also been demonstrated in different aspects of language, such as word reading (Kim 2022), sentence comprehension (Waters and Caplan 1996; Caplan and Waters 2005), language disorders (see Chapters 33–39 in Schwieter and Wen 2022a), second language acquisition (Altarriba and Isurin 2012), and semantic processing (Martin 2021). There have been several attempts in the literature to generalise the relationship between working memory and language and incorporate linguistic findings into working memory models, some of which are described below.

The influential multicomponent model (Baddeley and Hitch 1974) provides a direct link between working memory and language through the phonological loop. This component was initially described as a short-term store of verbal information, but it was later proposed (Baddeley et al. 1998) that the main evolutionary function of this component is to enable language acquisition due to its involvement in the ability to learn new words by both children and adults. For example, Gathercole and Baddeley (1990) found that phonological working memory was linked to the ability to learn new words in 5- to 6-year-old children. They measured memory capacity in a non-word repetition task and then asked children to learn familiar names (e.g. *Simon*) or non-names (e.g. *Sommel*) randomly assigned to toys. Children with lower working memory scores performed worse at learning non-names, whereas there was no effect of memory task scores on the learning of familiar names. Because the learning of non-names was assumed to imitate natural vocabulary acquisition, it was suggested that word learning is modulated by working memory. This view was supported by considerable evidence from numerous subsequent studies with clinical and healthy populations (see Baddeley 2003; Gathercole 2007; Szmalec et al. 2012 for reviews). Generally, data from patients with various language and/or memory impairments has contributed greatly to establishing the relations between various aspects of language processing and other cognitive functions. Studies involving patients with different language impairments, memory impairments or both language and memory impairments allowed researchers to dissociate different factors influencing performance on different tasks (Gathercole et al. 2006; Archibald 2017; Pierce et al. 2017; Martin 2021). It was found, for example, that, although phonological working memory is essential for novel word learning, it is not so much involved in language comprehension and production (Gathercole 2007; Martin 2021). Thus, several case studies of patients suffering from phonological memory deficits indicate that their ability to understand word meanings and comprehend sentences was not impaired (Martin and He 2004; Martin 2021). To account for these findings, Martin (2021) suggested further separation between semantic and phonological working memory buffers. In his domain-specific model, illustrated in Fig. 9, phonological representations can be accessed and rehearsed through the phonological buffer, whereas lexical and semantic representations are stored in a separate lexical-semantic buffer. The distinction between the two working memory components is also supported by neuropsychological data indicating that different brain areas are activated during tasks requiring phonological and semantic processing (see reviews in Martin et al. 2020 and Zahn et al. 2022).

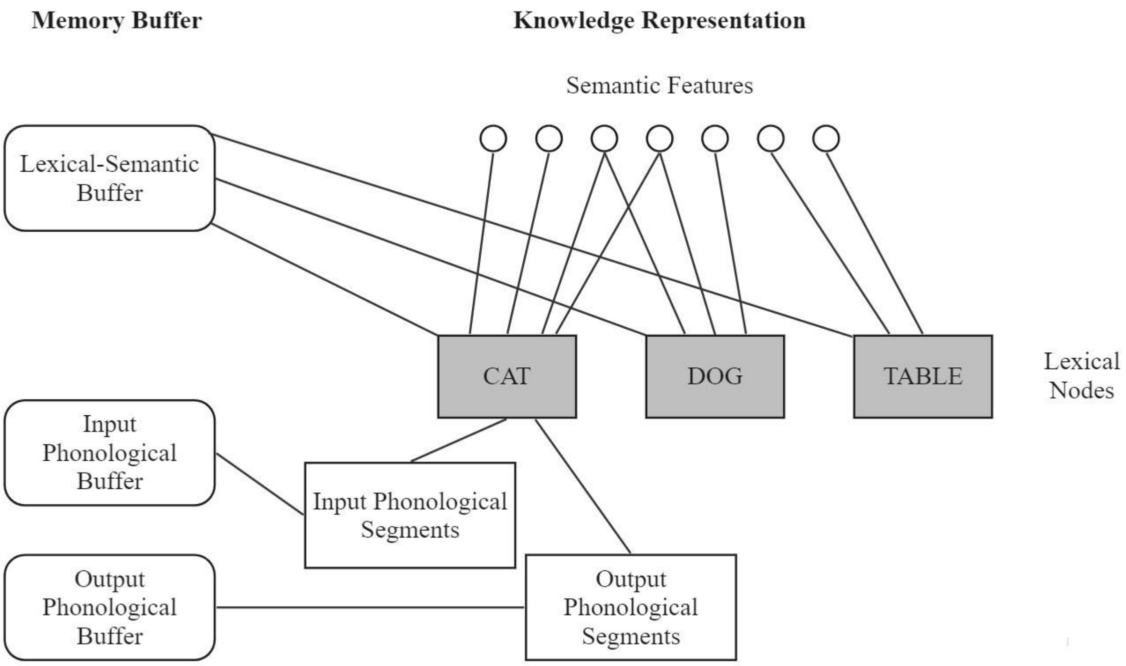

Fig. 9. The domain-specific working memory model (adapted from Zahn et al. 2022). Phonological items are linked to the phonological buffer, whereas lexical and semantic representations are linked to a separate lexical-semantic working memory buffer.

Consistent with the studies described above, a distinction between native and non-native language learning and language processing is also drawn in the "working memory as language aptitude" approach that crystallized into the Phonological/Executive Model (Wen 2019) schematically presented in Fig. 10. It posits that the limitedness of resources, which appears to be an inherent property of working memory, imposes restrictions on how language structures are shaped and processed. According to this model, the broad construct of working memory can be divided into two key components in relation to language: phonological working memory underpins the acquisitional and developmental aspects of native and non-native languages, whereas the executive working memory component subserves attentional mechanisms that control language processing. Distinguishing between these two working memory components also has important implications for second language acquisition research. Thus, the phonological component is domain-specific and plays an important role in vocabulary acquisition and grammar learning (Wen 2016; Pierce et al. 2017; also see Szmalec et al. 2012 for a review). In contrast, the executive component is domain-general, involves other executive functions, such as inhibitory control, task switching, and updating (Miyake and Friedman 2012) and contributes to high-level skills, such as semantics, sentence comprehension and production (Wen 2019).

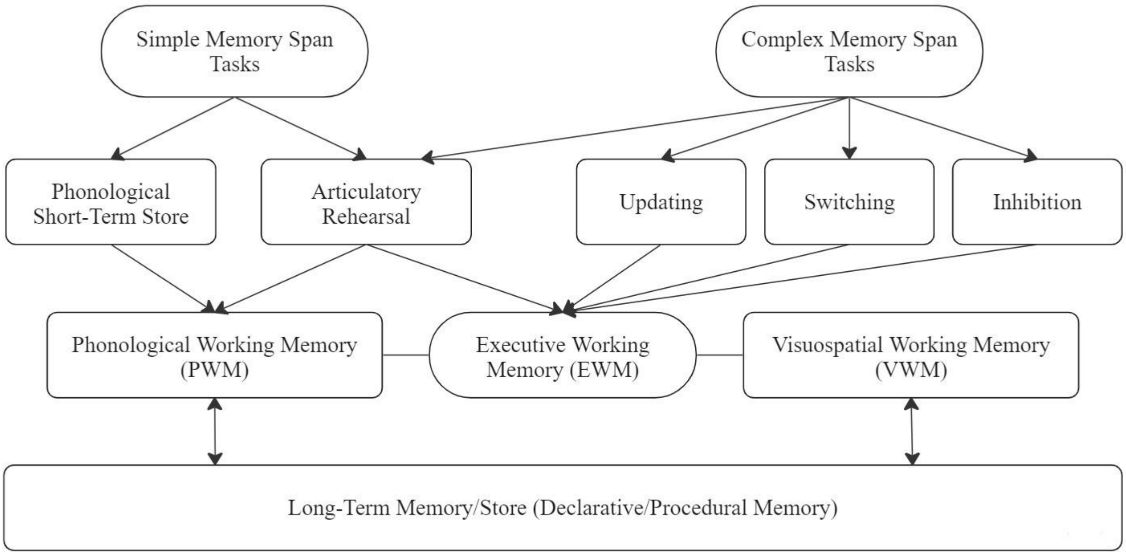

Fig. 10. The Phonological/Executive Working Memory Model (adapted from Wen 2019).

The role of working memory has often been studied in relation to bilingual language processing and second language acquisition (see Altarriba and Isurin 2012; Archibald 2017 for an overview). The fact that bilinguals need to control and switch between their languages has led to the idea that bilinguals might have better developed executive functions, in particular working memory, compared to monolinguals (Bialystok 2009). This so-called bilingual advantage hypothesis has been in the focus of many studies in the literature (Bialystok et al. 2012; Linck et al. 2014; Grundy and Timmer 2017; Lehtonen et al. 2018; Antón et al. 2019), but there is still no agreement whether knowing and using more than one language results in better domain-general working memory abilities. For example, a recent study by Antón et al. (2019) showed that the often-reported positive effect of bilingualism on general executive functions may be due to unrelated variables, such as socio-economic status, but they found a positive correlation between the bilingualism status and performance on some difficult versions of working memory tasks. There is a considerable body of research in this area, but the interaction between working memory and bilingualism is outside the scope of this thesis. Although Study 3 presented in Chapter 5 compared semantic processing in the native and non-native language, it did not include a manipulation of working memory load.

2.5. Spatial and verbal working memory

Similar to the debate about the separability of working memory from other executive functions (Miyake et al. 2000; Friedman and Miyake 2017; Karr et al. 2018; Glisky et al. 2021), there is also discussion about the specificity of spatial and verbal working memory. The influential multicomponent model (Baddeley and Hitch 1974; also see Section 2.3.1 above) makes a clear distinction between two components dealing with processing information of different modalities, namely the phonological loop (verbal) and the visuospatial sketchpad (spatial). In contrast, the embedded-processes model (Cowan 1988, 2010; Cowan et al. 2020; also see Section 2.3.2 above) makes no such distinction because activation of individual items in working memory is feature-based rather than modality-based. Despite different approaches, however, there appears to be a general consensus that there are two types of working memory that can be differentiated by content (Diamond 2013). The main area of discussion in the literature concerns questions about domain generality versus domain specificity with regard to working memory capacity, performance on various working memory tasks and the relationship between verbal and spatial working memory and other cognitive functions.

Evidence about the dissociation between two types of working memory usually comes from studies that use different tasks which are supposed to tax either the verbal or the spatial domain (Engle et al. 1999; Kane et al. 2004; Conway et al. 2005; Nagel et al. 2007; Swanson 2017). A general assumption is that if spatial working memory tasks can predict performance on spatial but not verbal ability measures and vice versa, it provides evidence for domain specificity of working memory. In contrast, if there is no distinction between the predictive power of spatial and verbal memory tasks, it will point to domain generality of working memory mechanisms. Shah and Miyake (1996) conducted two experiments to investigate the separability of spatial and verbal working memory resources across the processing and storage components. In the first experiment, they correlated performance on a spatial and a verbal span task with the composite spatial visualization score and the score on the standardized Verbal Scholastic Aptitude Test (SAT). The working memory tasks consisted of two parts that required both maintenance and processing of information at the same time. It was found that the measure of spatial working memory correlated only with the spatial ability scores, whereas the measure of verbal working memory correlated only with the verbal ability scores, but not vice versa. These findings supported the hypothesis about the domain specificity of working memory resources. In the second experiment, the processing components of the memory tasks were shuffled to either match or mismatch the domain of the storage component. In one of the mismatching conditions, for example, participants first had to judge the correctness of a sentence (processing component in the verbal domain) and then remember the orientation of an arrow (storage component in the spatial domain). The results confirmed previous findings regarding the separability of spatial and verbal working memory resources and provided evidence that performance on ability tests is mostly predicted by the nature of the storage component in working memory tasks although the processing component also plays an important role. These results are important for this thesis because Study 2 presented in Chapter 4 aimed to disentangle the effects of verbal and spatial working memory load on semantic processing. Based on the above findings pointing to the functional separation of spatial and verbal working memory resources, it was hypothesised in Study 2 that semantic processing would be more strongly affected by working memory load in the verbal domain, which is relevant for the task involving language processing.

Additional insight into the mechanisms of spatial and verbal working memory is provided by studies using simple span tasks. Unlike complex span tasks that require simultaneous maintenance and processing of information, simple span tasks are believed to impose demand only on the storage component of working memory. The most common simple span tasks include the digit span task for verbal memory, which involves remembering and recalling sequences of digits, and the Corsi span task for spatial memory, which involves memorizing sequences of blocks (see Donolato et al. 2017 for a review). Depending on study design, participants can be asked to recall items in the order of presentation or in the reverse order. A meta-analysis of 54 studies that used simple span tasks with forward and backward order of recall (Donolato et al. 2017) demonstrated differences between performance on verbal and spatial memory tasks: participants performed consistently better on forward than on backward verbal tasks, but there was no clear-cut distinction in performance on forward and backward visual recall tasks. There is also neurophysiological evidence that spatial and verbal working memory tasks are supported by different neural circuitry. Whereas greater brain activity is observed in the left hemisphere during verbal working memory tasks, spatial working memory tasks result in greater activity in the right hemisphere (Smith et al. 1996; Nagel et al. 2013).

The differences between verbal and spatial working memory were also illustrated in the studies of working memory capacity. For example, Kane et al. (2004) administered a battery of simple and complex span tasks, both in the verbal and spatial domain, as well as several tests to measure verbal and spatial reasoning and fluid intelligence. In their confirmatory factor analysis, the tests of spatial and verbal working memory showed a high correlation suggesting that what they measure is domain-general rather than domain-specific abilities. Furthermore, domain-general intelligence scores were strongly predicted by the working memory capacity measured in complex span, but not in simple span tasks. Although Kane et al. (2004) believe that this is due to the inseparable nature of working memory resources, an alternative explanation is that this pattern may be explained by individual differences in high-order executive attention (Mashburn et al. 2020).

The above studies focused mostly on the correlation between different types of working memory and other cognitive abilities. However, the assumptions about domain specificity and limited capacity of working memory led to the hypothesis that manipulating working memory load only in one domain may have selective impact on other executive functions that require verbal or spatial resources (e.g. Kim et al. 2005; Zhao et al. 2010; Clouter et al. 2015). Kim et al. (2005) conducted a series of experiments to investigate the effect of the type of working memory load on the Stroop interference effect. In the original Stroop task (Stroop 1935), participants were presented with names of colours printed in either congruent or incongruent colours (e.g. the word *red* printed in red colour versus the word *red* printed in blue colour). Participants were significantly faster and more accurate naming the colour of the word when it matched the meaning of the word than when it did not. The Stroop task, along with its many variations, is a common measure of inhibitory and selective attentional control. It is generally assumed that the interference effect is caused by the need to suppress the irrelevant information of the distractor and focus only on the relevant information of the stimuli (see Lu and Proctor 1995). Kim et al. (2005) designed various Stroop tasks and working memory tasks in such a way that the modality of the working memory tasks did or did not overlap with the modality of targets or distractors in the Stroop tasks. They demonstrated that it was not the working memory load itself, but rather the type of working memory involved that caused differences in the Stroop effect (cf. Ortells et al. (2018) for an effect of working memory load on Stroop interference, but Gao et al. (2007) for lack of such an effect). When the Stroop task contained verbal targets, the interference was larger in the verbal than in the spatial working memory load condition. Notably, the interference was significantly smaller when the distractors in the Stroop tasks matched the modality of the working memory task. It suggests that domain-specific working memory load may exhaust resources needed for inhibitory control and selective processing of targets and distractors. This pattern of results was later confirmed in an auditory Stroop task with verbal and spatial working memory load (Riffle and DiGiovanni 2017). The role of individual differences in working memory capacity and the importance of working memory resources for dealing with irrelevant information was also demonstrated in other studies involving Stroop tasks with congruent or incongruent prime-target pairs (Ortells et al. 2016, 2017; Fernández et al. 2021).

Another widely-used task that illustrates the importance of executive control and uses congruent and incongruent stimuli is the Simon task (Simon and Small 1969). In the original task, participants had to press a left or a right key in response to high- or low-pitched auditory stimuli. The sounds were presented randomly to the left or to the right ear, but the side of the presentation was not relevant to the task. Similarly to the Stroop task, participants showed an interference effect when the correct key was not congruent with the location of the sound. The effect was also replicated in other variations of the task using spatial stimuli (see Lu and Proctor 1995).

The interaction between the interference effect in a spatial Simon task and the type of working memory load was examined by Zhao et al. (2010). In their experiments, they implemented a dual-task paradigm, in which the Simon task was embedded in a spatial or verbal working memory trial. The verbal working memory task involved remembering a number of Chinese characters before the Simon task. After the Simon task, participants were presented with one character and had to respond if it was among the previously presented items. The spatial working memory task involved remembering and later recalling the location of squares (Experiment 1) or Chinese pseudocharacters (Experiment 2). The control conditions included only the Simon task without the working memory trials. In both experiments, there was a main effect of working memory task on response times in the Simon task. Furthermore, it was found that the interference effect in the Simon task disappeared under verbal working memory load, but it was not affected by the spatial working memory load. A possible explanation of this somewhat counterintuitive result is that different executive mechanisms may be responsible for representing spatial locations in the Simon task and maintaining them in the working memory task. Zhao et al.'s (2010) unexpected findings led Clouter et al. (2015) to further investigate the temporal distribution of the Simon effect as a function of working memory load and the type of working memory involved in the task. They accounted for some of Zhao et al.'s (2010) limitations by using the same stimuli in the spatial and working memory task. In the spatial condition, participants had to remember the location of letters on the screen, whereas in the verbal condition they had to remember the letter identity. The task difficulty was also manipulated using the *n*-back paradigm (see Kane et al. 2007 for an overview). In *n*-back tasks, participants are asked to match the currently presented item against the item presented n trials before. The larger *n*, the more demanding the task is believed to be. In Clouter et al.'s (2015) study, the 0-back spatial and verbal tasks represented low load, whereas 2-back tasks imposed high working memory load. The results showed that the Simon effect was smaller when working memory was taxed in high-load relative to low-load tasks. Furthermore, a distribution analysis also showed a different pattern of the interference effect under verbal and spatial working memory load. Overall, their findings suggested that the Simon effect was modulated both by the type of working memory task and the working memory load.

2.6. Conclusions

Research into working memory has received much attention from cognitive psychologists, neuroscientists and psycholinguists over the last several decades, which is indicative of the important role this executive function plays in the cognitive system in general and in language processing in particular. In this chapter, several theoretical accounts of working memory have been summarised showing a number of converging points across the various approaches. For example, working memory is generally viewed as a limited-capacity system, which is essential for performing task-oriented actions and which is highly dependent on attentional resources and linked with long-term memory. Some of the working memory mechanisms are specific to the processing of phonological and semantic information, which points to the close relationship between working memory and language. Crucial evidence for this relationship comes from research that disentangled verbal and spatial working memory resources. The findings from studies that differentiated between these two types of working memory (Shah and Miyake 1996; Kane et al. 2004; Kim et al. 2005; Conway et al. 2005; Nagel et al. 2007; Zhao et al. 2010; Clouter et al. 2015) suggest that taxing working memory in the verbal or spatial domain may have an effect on other cognitive processes involving verbal or spatial information, respectively. This distinction led to one of the main research questions of this thesis concerning the influence of spatial and verbal working memory load on semantic processing. Based on previous research, additional working memory load in the shared verbal domain was expected to affect semantic relatedness judgements more strongly than task-irrelevant spatial working memory load. To examine this, two versions of a working memory task were developed that taxed either spatial or verbal working memory and were presented to participants in a dual-task design with a semantic relatedness task. The experiment is reported in Section 4.2 and summarised in detail in Section 6.2.

Chapter 3: Polish word associations (Study 1)

3.1. Introduction

Recently, a Polish semantic priming database has been developed that consists of strongly related, weakly related and unrelated word pairs (Rataj et al. 2023). The degree of semantic relatedness between primes and targets was estimated using semantic spaces (see Section 1.2.3) and verified in two surveys that differed only in the order of prime-target presentation.

Rataj et al.'s (2023) dataset provides a solid benchmark for further semantic priming studies involving Polish stimuli. However, one limitation of this study is that it deliberately makes no distinction between associative and semantic relations. According to the literature (see Section 1.4 for an overview), the former mostly rely on how frequently different words appear together in spoken/written language, whereas the latter involve common features of word meanings. Although there is little consensus about the exact role of associative and semantic links in meaning processing, it is important to understand the nature of the relationship between stimulus words in linguistic studies to be able to draw more precise conclusions about factors influencing language processing.

A common way to establish the strength of associations between words is by using association norms from large-scale databases. Although such norms are available for English and several other languages thanks to studies involving large numbers of stimulus words and participants (De Deyne et al. 2013, 2018; Cabana et al. 2023), there is a lack of such data for the Polish language. Prior studies involving Polish (Kurcz 1967; Gawarkiewicz et al. 2008; Gatkowska 2015, 2016) included a relatively small number of cue words and differed in their methods of collecting associations, making it practically impossible to establish reliable measures of associative relations for a larger lexical sample (see Section 1.4 for an overview).

This chapter describes a free word association study that establishes association norms for the set of Polish stimuli from Rataj et al. (2023). The same stimulus set will be used in Study 2 to investigate the impact of working memory load on semantic processing (see Chapter 4). Therefore, it is crucial to make sure that the facilitation effects, which were observed in the lexical decision task by Rataj et al. and which were anticipated in a semantic relatedness task in Study 2, are due to semantic rather than associative links between primes and targets.

3.2. Aims, research questions and hypotheses

The primary aim of the study was to collect and analyse word associations to a set of Polish words. The experimental task was similar to a large-scale online study designed to collect word associations in other languages (De Deyne et al. 2019). Similarly to De Deyne et al., participants provided three associations to each cue word. The collected associations were then compared against words that were semantically strongly or weakly related to the cues (Rataj et al. 2023) to check whether semantically related words are also related associatively. To further explore the relationship between semantic and associative features, semantic similarity measures for cue-response pairs were calculated based on semantic spaces (see Section 1.2.3). These vector-derived values were then correlated with association-based measures.

The main research questions addressed in this study were as follows:

(1) Are semantically related words from a semantic priming dataset also related associatively?

(2) What is the relationship between human-obtained association norms and vector-based semantic similarity measures?

Prime-target pairs in Rataj et al. (2023) were selected based on semantic vectors and verified by human ratings of semantic relatedness, but, for the lack of objective measures of associative relatedness, it was not clear if some of them were also associatively related. This study tested experimentally whether prime-target pairs included close associates. If associations generated by prime words do not include semantically related target words, it will provide evidence that the priming effects observed in prior (e.g. Experiment 2 in Rataj et al. 2023) and future (Study 2, Chapter 4) studies using the same stimulus set are due to semantic and not associative links between primes and targets. More generally, it will also support the approach that encourages distinguishing between semantic and associative relations (Lucas 2000; Perea and Rosa 2002; Hutchison 2003). If, however, associations in the present study frequently coincide with semantically related targets from the original dataset, it will suggest that associative and semantic relations are closely intertwined and separate conclusions regarding either of them cannot be made in priming studies using the same dataset.

There is some evidence that association norms can serve as predictors, or at the very least as correlates, of lexical and semantic measures in psycholinguistic tasks (see Section 1.2.2). For example, De Deyne (2019) showed that English word association norms are better predictors of human performance on semantic tasks than word frequencies. On the other hand, corpus-derived values of semantic similarity have also been found to predict human performance on various linguistic tasks (Mandera et al. 2015a, 2017; Rataj et al. 2023; also see Section 1.2.3). In the present study, it was expected that association measures would correlate with semantic similarity values obtained from corpus-based semantic spaces. In particular, it was hypothesised that more strongly associated pairs will also be more similar in meaning and vice versa. It was further assumed that there would be a by-subject correlation between association strength and semantic similarity, i.e. participants who provided more common associations would respond with words that are closer in meaning to the cue words.

3.3. Method

The study was conducted fully online. The website http://associations.edu.pl/ was developed using the Angular front-end technology. It contained information for participants, informed consent, a questionnaire, instructions, and the association task itself. The website was developed based on recent crowdsourced online projects that allow the collection of larger sets of data as opposed to traditional lab-based experiments (Keuleers and Balota 2015; De Deyne et al. 2019). The idea behind the web-based study was to make it as easy and user-friendly as possible for participants to take part in the study. The website was created using responsive web design, meaning that participants could take part using any device with the Internet access and a browser, including tablets and mobile phones.

3.3.1. Participants

Participants included 484 native Polish speakers with a minimum age of 18 years. They were recruited through social media and the participant recruitment system at Adam Mickiewicz University in Poznan. Because the task required the participants to provide prompt responses, participants who took inadequately long to complete the experimental part were excluded from the analysis. In total, the data from 22 participants, whose duration fell outside 1.5 times the interquartile range above the upper quartile (1061 ms), were removed. The final sample included 462 participants (335 women, 10 preferred not to state, M_{age} = 21.8 years, SD_{age} = 4.1 years, maximum 54 years). The mean duration of the association task for the remaining participants was 508 sec (min. 193 sec, max. 1051 sec, *SD* = 184 sec). The breakdown of participants' education level is presented in Fig. 11. According to self-reports, 459 participants (99%) knew at least one foreign language, 402 (87%) at least two foreign languages, and 171 (37%) at least three foreign languages.

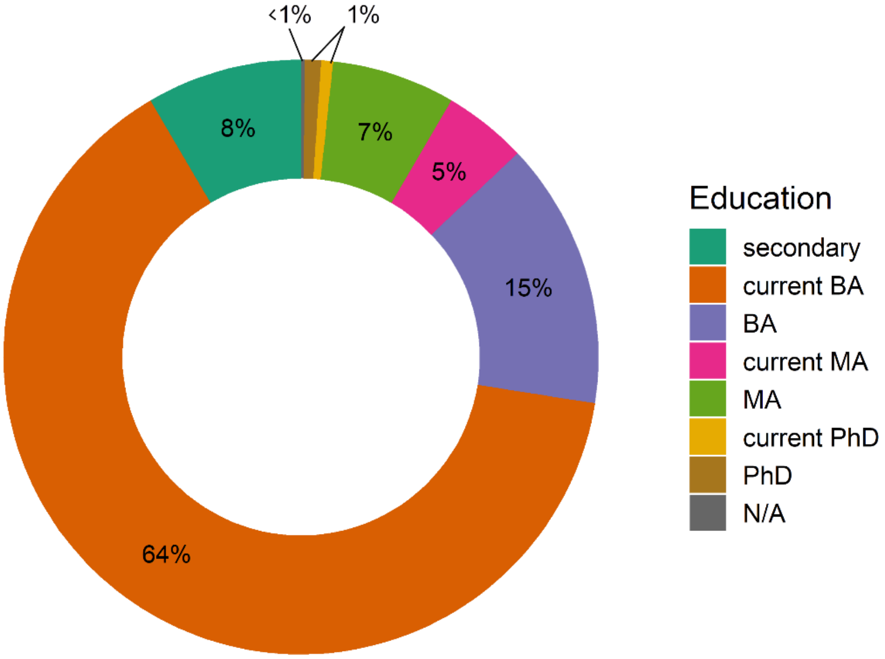

Fig. 11. Education levels of participants in Study 1.

3.3.2. Materials

The stimuli for the experimental part were taken from the set of Polish words created by Rataj et al. (2023). The set includes 216 target words and three prime words for each target: a strongly related (e.g. *hip* – *KNEE*), a weakly related (e.g. *muscle* – *KNEE*), and an unrelated one (e.g. *office* – *KNEE*). For the present study, only strongly and weakly related primes were included, which resulted in 432 words that served as cue words in the present study. They were divided into 18 lists each consisting of 24 words. The words were pseudorandomized across lists with the condition that no list included strongly and weakly related primes to the same target word from the original set. Each participant was assigned to the list with the lowest number of responses so far (if there were several lists with the same number of participants, one of such lists was selected randomly), so the total number of participants per list was levelled out, ranging from 23 to 27 after removing outliers. The order of words within the list was randomized.

3.3.3. Procedure

The study started with a welcome page that included brief information about the study and pre-conditions for participation. Here and on the following screens, participants could proceed by clicking the Next button. The next page presented eligibility criteria as well as ethical and informed consent statements. At this stage, participants could choose to agree or disagree with the terms by clicking the respective buttons. If they disagreed, they were taken back to the welcome page. If they agreed, they moved on to the demographic questionnaire. It included mandatory questions about age (validated to be at least 18), sex, current or highest education level, and major. Optionally, participants were also asked to indicate foreign languages they knew.

On the next page, detailed instructions for the word association part were shown. It was specifically stated that participants should avoid writing several words for a single association and providing associations to their previous responses. Some examples were also provided. After clicking the Next button, participants saw the first word from the assigned list.

On pages with cue words, numbered lowercase words (Roboto, 22px, bold) were presented horizontally aligned, and below the target word there was an input field where participants could enter their association. For each cue word, participants were instructed to provide three word associations which corresponded to three separate input fields displayed on separate pages. This design was used to prevent participants from providing chain responses, i.e. associations to their previous associations rather than the cue word, which might be the case if previous responses remained on the screen. After the participant entered the third association to the last word in the list, a send button appeared, which submitted their results to a server. A thank you page appeared after the results were submitted.

The anonymous data could be downloaded by the experimenter using the website's password-protected admin section as a csv file that included the following fields: participant number, list number, item, item number and relatedness code from the original stimulus set, submission date and time, duration from entering the first association to result submission, total duration from clicking the first Next button to result submission, all data from the questionnaire, and three responses to each cue word.

3.4. Results and discussion

The final dataset included 33,264 responses to 432 cue words. All entered responses were converted to lowercase, and entries indicating missing responses were filtered out, e.g. “don’t know” (*nie wiem*, *nie znam*), “nothing” (*nic*), “no” (*nie*), “no answer” (*brak*). Repeated responses to the same cue from the same participant were also deleted. There were six instances in which the second response was identical to the first one within the cue and participant, 11 instances in which the third response was identical to the second one, and four instances in which the third response was identical to the first one. As a result of data cleaning, one first response, 10 second responses and 25 third responses were removed (0.1% in total).

3.4.1. Novel responses

Participants’ responses were checked against the SUBTLEX-PL corpus (Mandera et al. 2015b) to identify potential non-words or novel responses. Precise instructions along with examples ensured that there were few (*N* = 687, 2.1%) responses that were not found in the corpus. They were manually analysed to see whether there were any regularities. In fact, most of the “inadequate” responses turned out to be existing words – for example, almost half of the responses (*N* = 314, 46%) not found in the corpus included two or more words that often referred to a single concept, e.g. *piłka nożna* (football), *bułka tarta* (bread crumbs), *centrum handlowe* (shopping mall), *strona internetowa* (website), *jabłko Adama* (Adam’s apple). At the same time, there were some descriptive responses including multiple words, e.g. *coś cienkiego* (something thin), *niemiły dźwięk* (unpleasant sound). Some other interesting examples included existing Polish words that were not in the corpus (N = 127, 18%), e.g. dialectal words (*oscypek* – smoked cheese from the Tatra Mountains region, *burchel* – blister in the Warsaw dialect), words referring to new phenomena (*Covid*, *Tiktok*), or very rare words, e.g. *głowotułów* (cephalothorax), *aglet* (aglet). There were also 110 words (16%) with typos, 66 (10%) proper names, 41 responses (6%) that included three valid words provided as one response (usually for the first cue word, which suggests that participants misunderstood the instructions), 15 responses (2%) with a wrong use of Polish diacritics, 7 (1%) non-existent words (e.g. *wpadaburza*, *czerepaszka*), and 7 (1%) responses that did not fall into any of the above categories (e.g. *scrapbooking*, *puzzle?*). Not only do these examples give an overview of marginal responses, but they also provide an indication of what kind of words are missing from widely used corpora. Because the number of non-matching entries was relatively low and most of them included existing words, they were not removed from further analysis.

3.4.2. Lexical characteristics

Lexical characteristics of the responses were obtained from SUBTLEX-PL (Mandera et al. 2015b). Zipf values, which are a standardised measure of word frequency (van Heuven et al. 2014), demonstrate that participants came up with less frequent words with every subsequent response (see Table 4 in Section 3.4.3 for a summary of response characteristics). The overall mean frequency of 3.81 (Zipf scale, approximately 6.5 pmw) corresponded to medium-frequency words and was slightly above the mean value of 3.72 for the SUBTLEX-PL corpus.

The part-of-speech distribution of responses (see Table 2) was also obtained from the same corpus. As is usually observed in free association studies (De Deyne et al. 2013; Gatkowska 2015), most of responses were nouns (87.9%), but their proportion was even greater than in the above studies (69.1% and 72%, respectively). Because the responses were to be subsequently matched with semantically related targets, which were also nouns, it was in fact preferable that participants would give as many noun associations as possible. To obtain free associations, there was no explicit mention of parts of speech in the instructions, but the examples provided were all nouns, which might have primed the participants. The instructions did however explicitly encourage participants to provide single-word associations and use Polish diacritics.

Table 2. Part-of-speech distribution of first (R1), second (R2), and third (R3) associations.

Part of speech	R1	R2	R3
adjective	443	589	622
adverb	139	129	129
conjunction	1	0	0
noun	10022	9700	9506
numeral	12	14	17

predicative	1	4	4
preposition	0	3	0
pronoun	2	1	0
particle-adverb	6	12	20
unknown form	5	5	6
undefined	214	229	276
verb	243	401	508
alien form	0	1	0

3.4.3. Types and tokens

For additional analysis, Polish diacritic signs were replaced with the corresponding Latin letters. The raw frequency, i.e. how many times a particular response occurred across all participants, was then calculated for first, second and third associations, and for all associations combined. Ten most frequent types and their frequencies are shown in Table 3.

Table 3. Most frequent responses provided as first (R1), second (R2), or third (R3) association and for all associations combined (R123) and number of their occurrences.

R1		R2		R3		R123	
Response	No.	Response	No.	Response	No.	Response	No.
jedzenie (food)	141	woda (water)	126	las (forest)	82	woda (water)	339
woda (water)	137	las (forest)	119	ból (pain)	82	jedzenie (food)	271
zwierzę (animal)	120	dom (home)	71	woda (water)	76	las (forest)	252
ptak (bird)	110	ból (pain)	70	jedzenie (food)	70	dom (home)	234
dom (home)	94	morze (sea)	67	dom (home)	69	ból (pain)	225
ryba (fish)	91	drewno (wood)	67	drewno (wood)	58	zwierzę (animal)	221
ciepło (warmth)	88	jedzenie (food)	60	ciepło (warmth)	53	drewno (wood)	199
ciało (body)	86	zwierzę (animal)	59	praca (work)	45	morze (sea)	185
drzewo (tree)	82	praca (work)	50	choroba (disease)	45	ciepło (warmth)	183
morze (sea)	78	ciało (body)	47	obiad (lunch)	44	ciało (body)	165

The most frequent responses included very common words referring to everyday objects or common needs. Remarkably, two out of three most frequent associations for Polish, i.e. *woda* (water), *jedzenie* (food), and *las* (forest) were the same as most frequent tokens in English (*money, food, water*; De Deyne et al. 2019) and in the Rioplatense variety of Spanish spoken in Argentina and Uruguay (*water, food, love*; Cabana et al. 2023). The opposite end of the frequency range is represented by the so-called *hapax legomena* – words that appeared only once among responses. The percentage of such responses is summarised in Table 4 for first, second and third associations, and for all associations combined, indicating how often unique responses were provided. The mean percentage of such unique responses for the dataset including all three responses was 52.9%, which is comparable to English (57.3%; De Deyne et al. 2019) and Rioplatense Spanish (61%; Cabana et al. 2023) data. The percentage of unique responses was higher for third responses (60.8%) than for first (57%) or second (57.4%) responses, indicating that participants came up with more unconventional words for more distant associations.

Next, type-to-token ratios (TTR) were calculated as an index of lexical variability separately for first, second and third associations, and for all associations combined. The results are summarised in Table 4. TTR was calculated by dividing the number of unique responses (types) by the total number of responses (tokens). A high TTR indicates a large degree of diversity in association responses, whereas a low TTR indicates that participants were more repetitive in their responses.

Table 4. Characteristics of responses for first (R1), second (R2), third (R3) associations and all associations combined (R123). Values in parentheses indicate standard deviation.

	R1	R2	R3	R123
Zipf value	3.92 (0.81)	3.78 (0.83)	3.73 (0.85)	3.81 (0.83)
Percentage of hapax legomena, %	57.0	57.4	60.8	52.9
No. of types	2771	3586	4085	6543
No. of tokens	11088	11088	11088	33264
Type-to-token ratio	0.25	0.32	0.37	0.20
Match percentage with semantically related targets, %	1.62	0.60	0.44	2.66
Association strength relative to cue word	0.21 (0.16)	0.09 (0.04)	0.07 (0.02)	0.12 (0.12)
Similarity value relative to cue word	0.35 (0.1)	0.30 (0.08) 0.25 (0.06)*	0.27 (0.07) 0.22 (0.05)**	0.30 (0.09)

Note.
* Similarity between R2 and R1
** Similarity between R3 and R2

Subsequently, the responses were aggregated by cue word and the TTR was calculated for each of them. Five cue words with the lowest and highest TTRs are shown in

Table 5 and Table 6, respectively, along with the number of types and three most frequent responses to respective cue words. Low TTRs indicate that participants were highly consistent in their associations, whereas high TTRs suggest that participants' associations were more diverse.

Table 5. Cue words with the lowest type-to-token ratios.

Cue word	Type-to-token ratio	No. of types	Most frequent responses	No. of occurrences
prześcieradło (bedsheet)	0.26	21	łóżko (bed)	24
			pościel (linen)	13
			sen (sleep)	10
wymiona (udder)	0.27	22	krowa (cow)	27
			mleko (milk)	21
			dojenie (milking)	6
kciuk (thumb)	0.28	23	palec (finger)	21
			dłoń (palm)	16
			ręka (hand)	14
drzazga (splinter)	0.28	23	ból (pain)	21
			drewno (wood)	20
			palec (finger)	9
opatrunek (bandage)	0.28	23	rana (wound)	18
			bandaż (bandage)	13
			krew (blood)	9

Table 6. Cue words with the highest type-to-token ratios.

Cue word	Type-to-token ratio	No. of types	Most frequent responses	No. of occurrences
łącznik (connector)	0.79	62	połączenie (connection)	7
			kontakt (socket)	3
			kabel (cable)	3
wstrząs (shock)	0.75	56	ziemia (earth)	4
			wypadek (accident)	4
			trzęsienie (quake)	3
wioska (village)	0.73	59	wieś (village)	4
			pole (field)	4
			spokój (peace)	3
podesty (platform)	0.73	55	schody (steps)	11
			podwyższenie (elevation)	4
			wysokość (height)	3

powłoka (coating)	0.73	59	warstwa (layer)	7
			ochrona (protection)	4
			skorupa (shell)	3

3.4.4. Associatively versus semantically related words

The cue words in the present study were also prime words in Rataj et al.’s (2023) study and had strong or weak semantic links with the target words from the original stimulus set. The main aim of this study was to check whether semantically related target words were among associations generated in response to a cue. For this purpose, association responses were matched against semantically related targets to see how often the target word occurred among participants’ associations. Overall, there were 54 cue words (see Appendix A) for which the semantically related target word appeared at least once as first, second or third association, including 48 words that were strongly related primes and six words that were weakly related primes in the original study. The cue words, for which semantically related targets accounted for at least 30% of associations regardless of the order of responses, are presented in Table 7. All these cue words were strongly related primes in Rataj et al.’s word triplets. The match rate was calculated as the number of times the target word was provided as first, second or third response divided by the total number of responses to the given cue word. The overall match rate was calculated as the number of times the target word was provided as response regardless of the order divided by the total number of participants that provided associations to the given cue word. Thus, for example, all participants provided *okulary* (glasses) as an association to *oprawki* (glasses frame) and it was their first association in 96% of cases and their third association in 4% of cases. The mean percentage of matches between associations and target words is provided in Table 4. Overall, only 2.66% of association responses overlapped with semantically related target words in Rataj et al.’s study.

Table 7. Cue words with a more than 0.3 overall match rate between association responses and semantically related target words.

Cue word	Response / Target word	Overall match rate	R1 match rate	R2 match rate	R3 match rate
oprawki (glasses frame)	okulary (glasses)	1	0.96	0	0.04

odrzutowiec (jet)	samolot (plane)	0.79	0.67	0.08	0.04
niedopałek (cigarette end)	papieros (cigarette)	0.7	0.48	0.15	0.04
wybrzeże (coast)	morze (sea)	0.65	0.58	0.08	0
szkic (sketch)	rysunek (painting)	0.65	0.58	0.08	0
skoroszyt (workbook)	zeszyt (notebook)	0.58	0.54	0.04	0
przyśpiewka (refrain)	piosenka (song)	0.48	0.36	0.12	0
szrama (scar)	blizna (scar)	0.48	0.22	0.17	0.09
grzywka (fringe)	fryzura (haircut)	0.48	0.15	0.2	0.12
podesty (platform)	schody (steps)	0.44	0.36	0.04	0.04
płaszczka (stingray)	ryba (fish)	0.4	0.28	0.04	0.08
prostokąt (rectangle)	kwadrat (square)	0.37	0.26	0.07	0.04
kij (stick)	patyk (stick)	0.37	0.22	0.15	0
rozlewisko (flood waters)	jezioro (lake)	0.35	0.04	0.22	0.09
surdut (frock coat)	garnitur (suit)	0.31	0.19	0.04	0.08

3.4.5. Association strength versus semantic similarity

To further explore the relationship between associative and semantic similarity, association strength and semantic similarity values were determined for individual cue-response pairs. The association strength was calculated as the number of times a particular response was provided to the given cue word divided by the total number of responses to this cue depending on the order (first, second, third, or all responses combined). It reflects the probability with which a particular word will appear as first, second or third association to the cue word. Although TTR and association strength are interrelated, the TTR is a characteristic of the cue word, whereas the association strength describes the relation between the cue and individual responses. Association strength values averaged across cue words are summarised in Table 4 for first, second and third responses, and for all responses combined.

The notion of semantic similarity comes from the field of distributional semantics and natural language processing and is based on the assumption that words appearing in similar contexts have similar meanings (see Section 1.2.3). If word meanings are represented as vectors in a multi-dimensional semantic space, the distance between vectors may be considered to be an objective indicator of semantic similarity between concepts. Usually, the cosine distance is used for this purpose. The smaller the distance, the more similar two concepts; in contrast, the more orthogonal the vectors, the larger the cosine distance between them is and the less similar the concepts are.

In the present study, the *word2vec* vectors (Mikolov et al. 2013) from the nkjp+wiki-forms-restricted-300-cbow-ns.txt.gz semantic space (Mykowiecka et al. 2017, http://dsmodels.nlp.ipipan.waw.pl/) were used because this model had the highest performance rating for the dataset used in this experiment based on Rataj et al.'s (2023) ranking. Semantic similarity between word pairs was then calculated using the w2v program (https://github.com/waltervanheuven/w2v-model). Similarity values were determined for first, second and third responses, for all responses combined, as well as between second and first responses and between third and second responses. Mean values are summarised in Table 4.

Between-subject and between-item differences of similarity and association strength values for first (R1), second (R2), and third (R3) responses were tested in a one-way analysis of variance (ANOVA) using the afex package (Singmann et al., 2021) in R version 4.1.1 (R Core Team, 2021). The differences between R1, R2 and R3 were significant both for similarity ($F_1(1.96, 905.6) = 570.46$, $p < .001$, $\eta_p^2 = .55$; $F_2(1.59, 684.26) = 247.69$, $p < .001$, $\eta_p^2 = .37$) and association strength values ($F_1(1.2, 555.3) = 2839.28$, $p < .001$, $\eta_p^2 = .86$; $F_2(1.08, 466.03) = 327.29$, $p < .001$, $\eta_p^2 = .43$) with the highest values for R1, lower values for R2 and the lowest for R3. Post-hoc Bonferroni-corrected t-tests conducted using the emmeans package (Lenth 2021) revealed significant differences both between R1 and R2 ($t_1(461) = 21.95$, $p < .001$; $t_2(430) = 13.63$, $p < .001$ for similarity values; $t_1(461) = 50.63$, $p < .001$; $t_2(430) = 16.85$, $p < .001$ for association strength) and between R2 and R3 ($t_1(461) = 11.81$, $p < .001$; $t_2(430) = 10.21$, $p < .001$ for similarity values; $t_1(461) = 26.44$, $p < .001$; $t_2(430) = 13.55$, $p < .001$ for association strength).

The semantic similarity values were also correlated with associative strength and type-to-token ratio to investigate the relationship between human-generated associations and corpus-based semantic vectors. Correlation values between these three parameters are summarised in Table 8. An example visualisation of correlations is shown for first responses in Fig. 12.

Table 8. Correlation between semantic similarity, association strength and type-to-token ratio for first (R1), second (R2), third (R3) associations and all associations combined (R123) grouped by cue word. Values indicate Pearson correlation coefficients (*r*).

	Associative strength	Type-to-token ratio
R1 similarity	0.35	-0.32
R2 similarity	0.28	-0.27
R3 similarity	0.15	-0.17
R123 similarity	0.24	-0.25

Note. All correlations are significant with $p < 0.001$.

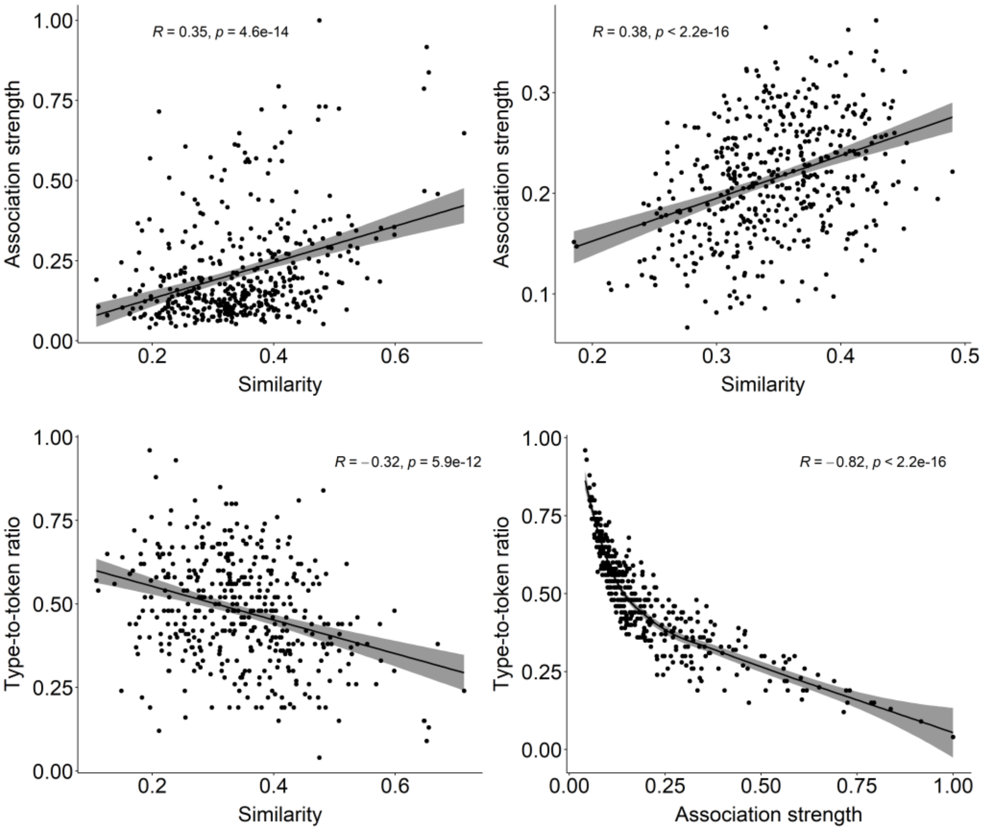

Fig. 12. Correlations between associative and semantic measures for first responses. Top left panel – by-item correlation between similarity values and association strength; top right panel – by-subject correlation between similarity values and association strength; bottom left panel – by-item correlation between similarity values and type-to-token ratio; bottom right panel – by-item correlation between association strength and type-to-token ratio.

Two plots in the top panel show positive correlations between the measures of associative and semantic similarity when responses were combined by participants ($R = 0.38$, $p < .001$) and by items ($R = 0.35$, $p < .001$). It suggests that more frequent association responses were also more semantically related to the cue words. The plot in the bottom left panel shows a negative (*R* = -0.32, *p* < .001) correlation between type-to-token ratios and semantic similarity, indicating that more consistent responses (i.e. those with lower type-to-token ratios) were also more semantically related. The plot in the bottom right panel compares two measures of associative relatedness and shows that the more likely the responses, the more consistently (*R* = -0.82, *p* < .001) they were provided in response to particular cue words (i.e. type-to-token ratios were lower). The implications of these findings are discussed in more detail in Section 6.2.

3.4.6. Response chaining and unconventional response patterns

One of potential caveats of asking participants to provide several responses to one cue word is that they might provide associations to their previous responses instead of the cue word. To check for possible response chaining, similarity values between first and second responses and between second and third responses were calculated for each cue word based on the same *word2vec* vectors and following the same approach as for obtaining the measures of semantic similarity between responses and cue words. Mean R2/R1 and R3/R2 similarity values were smaller than the means for either first or second responses (see Table 4). The paired-samples t-test confirmed that second responses were significantly more similar to cue words than to first responses, *t*(461) = 22.95, *p* < .001, and third responses were significantly more similar to cue words than to second responses, *t*(461) = 23.31, *p* < .001.

Similarity values can also provide an indication of how much actual responses differ from the expected pattern, following which second associations should be less similar to the cue word than first associations; third associations should be less similar to the cue word than second or first associations; and, provided that participants show no response chaining, second associations should be less similar to first associations than to cue words; and third associations should be less similar to second associations than to cue words. Table 9 shows mean differences in similarity values between the response pairs and the percentage of participants and targets that did not conform to the expected pattern.

Table 9. Mean differences between similarity values of responses depending on their order and percentage of participants and targets that showed unexpected response patterns.

	Participants	Targets
$R1_{sim} – R2_{sim}$	0.05	0.05
$R2_{sim} > R1_{sim}$, %	16.7	22.5
$R2_{sim} – R3_{sim}$	0.03	0.03
$R3_{sim} > R2_{sim}$, %	29.4	27.9
$R1_{sim} – R3_{sim}$	0.07	0.07
$R3_{sim} > R1_{sim}$, %	9.1	13.6
$R2_{sim} – R2/R1_{sim}$	0.05	0.05
$R2/R1_{sim} > R2_{sim}$, %	13.6	19.5
$R3_{sim} – R3/R2_{sim}$	0.12	0.12
$R3/R2_{sim} > R3_{sim}$, %	1.5	6.5

Note. $R1_{sim}$ – similarity between the first response and the cue; $R2_{sim}$ – similarity between the second response and the cue; $R3_{sim}$ – similarity between the third response and the cue; $R2/R1_{sim}$ – similarity between the second and the first response to the same cue; $R3/R2_{sim}$ – similarity between the third and the second response to the same cue.

The data shows that 16.7% of the participants generated second associations that were more similar to the cue than first associations, 29.4% of the participants generated third associations that were more similar than second associations, and 9.1% of the participants generated third associations that were more similar than first associations. Mean similarity values for first responses relative to the cue, and second responses relative to the cue and to first responses for a small sample of participants is presented in Fig. 13.

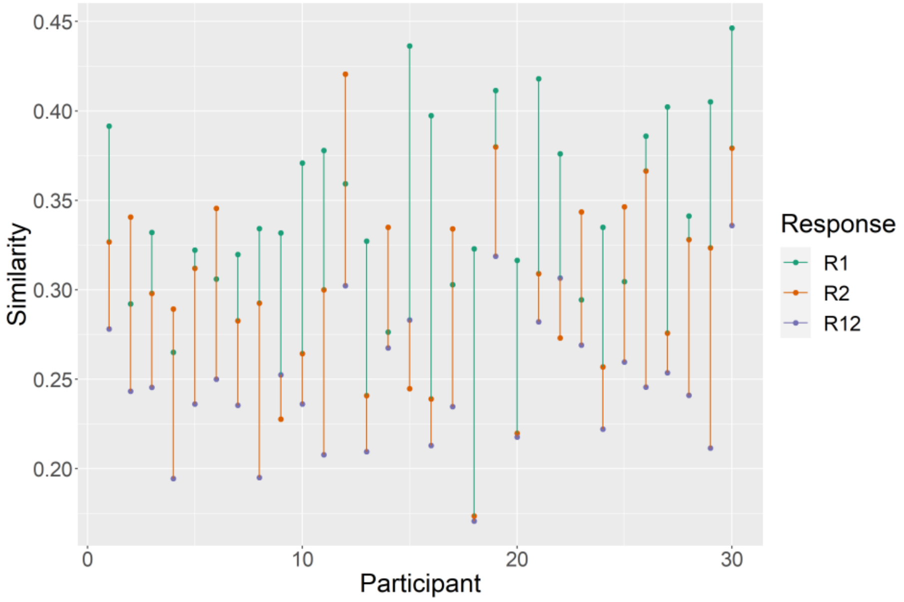

Fig. 13. Mean similarity values for first responses relative to the cue (R1), and second responses relative to the cue (R2) and to first responses (R12) for the first 30 participants.

Participants showing this unexpected pattern of responses might have resorted to a particular strategy of trying to come up with more original responses first and then contenting themselves with more “standard” ones. Alternatively, this pattern may be explained by non-linguistic reasons, for example, by participants’ recent experiences or memories. Potentially, although unlikely, these unconventional responses might characterise the structure of some participants’ semantic memory, with the fastest response being distantly related to the cue, and subsequent associations making use of stronger semantic links. Ultimately, however, these conjectures should be treated with a pinch of salt because vector-based similarity values are an abstract measure of semantic relations that is based on lexical co-occurrences in a corpus. Moreover, the differences in similarity values between individual responses were often very small, so the percentages of unexpected responses and response chaining might be inflated by insignificant or chance differences.

3.5. Conclusions

The primary goal of the present study was to obtain association norms for a set of Polish words and to compare free associations with semantically related word pairs from Rataj et al. (2023). To this end, more than 33,000 responses to 432 cue words were obtained through a custom-made website from more than 450 volunteers. Participants provided three different associations to each cue, which made it possible to analyse both stronger and weaker associations as well as potential response chaining.

The results provide crucial evidence that, for the majority of cues, semantically related target words from Rataj et al. (2023) never appeared among association responses. These findings support the distinction between semantically related words and word associations and give good reasons to state that it is semantic relations that contribute to facilitation effects of related versus unrelated pairs reported in studies using this Polish stimulus set (Rataj et al. 2023; Khanzhyn et al. in press).

One of the novelties of the present study was comparing corpus-based measures with human-generated word associations. Corpus-derived semantic vectors (Mykowiecka et al. 2017) obtained with *word2vec* (Mikolov et al. 2013) were used to calculate semantic similarity between participants' responses and cue words. It was found that there is a positive correlation between semantic similarity and association strength and a negative correlation between semantic similarity and type-to-token ratios. These results suggest the structure of semantic memory can be complementarily investigated using both network-based and corpus-based approaches (Mandera et al. 2017; Rataj et al. 2023).

The findings of the present study and their theoretical implications will be discussed in Chapter 6 (Section 6.2). In summary, Study 1 confirmed that most of the semantically related words from the tested dataset show a small degree of associative relation. Therefore, it provided evidence that these stimuli can be used to specifically investigate semantic relations. It is important for the present project because Study 2 described in the following chapter used the same stimulus materials to explore the role of working memory load in semantic processing. Furthermore, Study 1 demonstrated that the measures of associative relatedness obtained from human-generated data correlate with the measure of semantic similarity calculated using semantic vectors.

Chapter 4: The impact of spatial and verbal working memory load on relatedness judgements (Study 2)[1]

4.1. Introduction

As discussed in Chapter 2, working memory is one of executive functions that is crucial for language processing. However, there has been limited research into the influence of working memory on semantic processing (see Section 1.3.3). Whereas some studies used the semantic relatedness task to explore semantic processing (Balota and Paul 1996; Faust and Lavidor 2003; Kuperberg et al. 2008; Ortu et al. 2013; Gilbert et al. 2018; Poort and Rodd 2019; also see Section 1.4), these did not investigate the impact of working memory. In contrast, studies that focused on working memory did not distinguish between spatial and verbal domains and used the semantic priming lexical decision task with related and unrelated word pairs (Heyman et al. 2015, 2017). The present study consists of three experiments that used the semantic relatedness task to investigate the impact of the type of working memory (spatial vs verbal) and working memory load (low vs high) on semantically strongly related, weakly related and unrelated word pairs. These pairs were confirmed to be mostly semantically related and not associated in Study 1 (Chapter 3), so Study 2 focuses specifically on the impact of working memory on semantic relatedness.

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[1] Part of this chapter is based on a paper that focuses on Experiment 2.1 (Khanzhyn, Dmytro, Walter J. B. van Heuven and Karolina Rataj. In press. “The impact of spatial and verbal working memory load on semantic relatedness judgements”, *Psychonomic Bulletin & Review*).

In Experiment 2.1, participants performed a dual task in which a semantic relatedness judgement task was interleaved with a spatial or verbal working memory task. Experiments 2.2 and 2.3 were control experiments without a working memory task that differed in terms of procedure.

4.2. Relatedness judgements with working memory load (Experiment 2.1)

As discussed in Section 1.3.3, previous studies on the impact of working memory load on semantic processing showed divergent results (Heyman et al. 2015, 2017). According to Heyman et al. (2017), one of the reasons for the inconsistent findings might be the non-verbal nature of the working memory task used in both studies. There has indeed been some evidence that verbal and spatial working memory load has a differential effect on various cognitive phenomena, such as long-term repetition priming (Baqués et al. 2004), Stroop priming (Ortells et al. 2017, 2018), and the Simon effect (Zhao et al. 2010; Clouter et al. 2015). The present experiment therefore used verbal and spatial tasks to investigate for the first time the effect of different types of working memory load on relatedness judgements.

Another novel aspect of this experiment is the manipulation of the strength of semantic relatedness between primes and targets. Lexical materials in most semantic priming studies are limited to related and unrelated prime-target word pairs. Assuming that the degree of relatedness between words is a continuous rather than a binary value, several studies used weakly related pairs (e.g. *window – stairs*) or semantically mediated word pairs (e.g. *lemon – [sour] – sweet*) to explore the nature of spreading activation and the semantic priming effect (e.g. McNamara and Altarriba 1988; Hill et al. 2002). Only two semantic relatedness studies have tested the intermediate relatedness condition (Kuperberg et al. 2008; Ortu et al. 2013). Even less numerous are studies using weakly related pairs in the Polish language. As far as I am aware, the only known semantic priming study with weakly related Polish word pairs was conducted by Rataj et al. (2023) who developed and used such stimuli in both a semantic priming lexical decision task and a rating study.

4.2.1. Aims, research questions and hypotheses

Considering the above research gaps, the overall aim of Experiment 2.1 was to investigate the impact of the working memory task type (spatial vs verbal) and load (low vs high) on relatedness judgements of semantically strongly related, weakly related and unrelated word pairs. Three key research questions were addressed in this experiment:

(1) Does working memory load (high vs low) impact semantic relatedness judgements?

(2) Does working memory type (verbal vs spatial) influence semantic relatedness judgements?

(3) Do working memory load and type affect relatedness judgements for words with different degrees of semantic relatedness in a similar way?

The first hypothesis concerned an overall effect of working memory load on relatedness judgements, i.e. participants were expected to be slower and less accurate in their responses when their working memory was taxed more. Previous findings suggest that imposing a high working memory load negatively affects performance on other cognitive and strategic activities. Thus, working memory load was found to affect the performance in lexical decision tasks (Heyman et al. 2015, 2017), the Simon effect (Clouter et al. 2015), and strategic processing in a Stroop-primed task (Ortells et al. 2017, 2018).

Furthermore, it was expected that there would be a difference between the verbal and the spatial working memory task in terms of impact on the judgements of related pairs relative to unrelated pairs because the verbal task would constrain resources in the domain that is relevant for semantic processing. Although there is some evidence of domain-specific effect of working memory load on non-linguistic tasks (Zhao et al. 2010; Clouter et al. 2015; Ortells et al. 2018), there is a lack of studies investigating the interaction between different working memory domains and language processing. Previous semantic priming studies that manipulated working memory did not specifically distinguish between its different domains. Although Heyman et al. (2015) found that high working memory load affected the priming effect for prime-target pairs with asymmetrical forward association, they did not distinguish between verbal and spatial domains and their findings were not replicated in a follow-up study (Heyman et al. 2017). At the same time, no significant influence of a secondary working memory task on the priming effect was reported for masked identity priming in a lexical decision task (Perea et al. 2018).

Following Rataj et al. (2023), who found a graded facilitation effect for strongly and weakly related pairs in a semantic priming lexical decision task, it was expected that target words preceded by strongly related words would evoke the shortest reaction times (RT), unrelated words the longest RTs, and the RTs for weakly related pairs would fall in-between.

It was also hypothesised that weakly related pairs would be more sensitive to the working memory manipulation due to weaker semantic links between primes and targets. There are no known findings on the interaction between working memory load and the degree of relatedness. However, Radel et al. (2015) also used stimuli with three levels of prime-target relatedness to investigate the effect of inhibition on lexical decisions targets preceded by weakly and strongly related words. Before the semantic priming lexical decision task, the level of inhibition demands was manipulated in Radel et al. using a Simon task, in which circles of different colours were presented on the right or on the left side of the screen. Participants were instructed to press the right or the left key depending on the colour of the circles and ignore their location. The experiment included two versions of the Simon task with a high or low number of incongruent trials. It was found that, after the participants were exposed to a high-inhibition task and their inhibitory resources were depleted, weakly related primes (e.g. *window – stairs*) led to a larger priming effect in the lexical decision task than after a low-inhibition task. This hyper-priming effect for weakly related primes under disinhibition conditions suggests that semantic activation can be modulated by control demands. If working memory manipulation in the present study significantly impacts the facilitation effects in the relatedness judgement task, it will support the assumption that semantic processing is not completely capacity-free and can be affected by high-order executive functions (Hutchison et al. 2014; Heyman et al. 2015; Radel et al. 2015).

4.2.2. Method

4.2.2.1. Participants

66 students of the Faculty of English of Adam Mickiewicz University in Poznan (58 women, 1 preferred not to state, M_{age} = 21.2 years, SD_{age} = 1.3 years) took part in the experiment. Data from four participants who gave less than 80% of correct responses to unrelated and strongly related pairs were excluded from analysis, which resulted in a final sample of 62 participants. None of them suffered from any reading disorders (self-reported), they were all native Polish speakers and received course credits in return for their participation.

4.2.2.2. Design

The experiment was designed using PsychoPy (Peirce et al. 2019) and conducted online on the Pavlovia platform (www.pavlovia.org), which enables the collection of high-precision behavioural data in web-based experiments (Bridges et al. 2020). The experiment consisted of two sessions separated by at least 7 days (maximum 23 days). In one session, participants performed a semantic relatedness task combined with a spatial working memory task; in the other session, the semantic relatedness task was combined with a verbal working memory task. Each session was divided into two blocks, each having a different level of working memory load (low vs high). The working memory load was manipulated using the n-back paradigm (Kane et al. 2007; Clouter et al. 2015). In the low-load block, participants had to remember the item (dot position or letter identity) from the previous trial (1-back). In the high-load block, participants had to remember the item from two trials before (2-back). The order of sessions and blocks within each session was counterbalanced across participants.

The experiment involved a 3 x 2 x 2 within-subject design with the independent variables: Relatedness (strongly related vs weakly related vs unrelated), Working Memory Task (verbal vs spatial), and Working Memory Load (low vs high). Response times and accuracy rates in the semantic relatedness and working memory tasks were the dependent variables. The experiment was approved by the Ethics Committee for Research Involving Human Participants at the Adam Mickiewicz University in Poznań (Resolution 32/2019/2020).

4.2.2.3. Materials

Semantic Relatedness Task

Stimulus materials (word pairs) for the semantic relatedness task were taken from Rataj et al. (2023). Critical Polish stimuli included 216 triplets consisting of a target word preceded by a strongly related word (e.g. *hip – KNEE*), a weakly related word (e.g. *muscle – KNEE*), and an unrelated word (e.g. *office – KNEE*). Further 16 unrelated word pairs were used as filler items that were presented after self-paced breaks in each block. Characteristics of the critical stimuli are presented in Table 10 and the list of critical word pairs is available at https://osf.io/2x8ka.

Table 10. Lexical characteristics of 216 word pair triplets: length, word frequency (Zipf values from SUBTLEX-PL), and the semantic relatedness values (cosine similarity scores) for the strongly related, weakly related, and unrelated conditions (from Rataj et al. 2023).

Characteristics	Mean	SD (min. - max.)
Target word frequency	3.6	0.4 (2.9 - 4.1)
Target word length	6.3	1.4 (4 - 9)
Word frequency (prime)		
strongly related	2.9	0.8 (1.1 - 5.5)
weakly related	3.2	0.8 (1.3 - 5.3)
unrelated	3.5	0.4 (2.9 - 4.7)
Word length (prime)		
strongly related	7.2	2.2 (3 - 15)
weakly related	6.4	1.8 (3 - 12)
unrelated	6.7	1.5 (4 - 9)
Semantic relatedness values		
strongly related	0.69	.07 (0.48 - 0.86)
weakly related	0.50	.05 (0.42 - 0.75)
unrelated	0.12	.13 (-0.18 - 0.51)

The stimuli were divided into eight lists, each containing 27 strongly related, 27 weakly related and 54 unrelated pairs with different targets. Twenty prime words were repeated across lists, but only in one case did the same prime word appear twice in the same list. Lists were assigned to participants so that targets did not repeat across blocks within each session. However, the same targets were repeated in the second session, but these were preceded by a different word. An example of task counterbalancing and list assignment for the first two participants is shown in Table 11. The lists were repeated in different blocks or sessions for every second participant. This design ensured more than 1,600 observations for the critical weakly and strongly related conditions in each working memory condition (27 * 62 = 1,674). According to Brysbaert and Stevens (2018), this is the recommended minimum for repeated-measures studies aiming to detect small effect sizes ($d = .1$) usually observed in RT experiments.

Table 11. Counterbalancing matrix of tasks and lists (SR – strongly related pairs, WR – weakly related pairs, UR – unrelated pairs).

Participant	Session 1 Block 1	Session 1 Block 2	Session 2 Block 1	Session 2 Block 2
1	*Low spatial WM*	*High spatial WM*	*Low verbal WM*	*High verbal WM*
	List A:	List E:	List C:	List G:
	SR 1–27	SR 109–135	SR 55–81	SR 163–189
	WR 28–54	WR 136–162	WR 82–108	WR 190–216
	UR 55–108	UR 163–216	UR 109–162	UR 1–54
2	*High verbal WM*	*Low verbal WM*	*High spatial WM*	*Low spatial WM*
	List B:	List F:	List D:	List H:
	SR 28–54	SR 136–162	SR 82–108	SR 190–216
	WR 55–81	WR 163–189	WR 109–135	WR 1–27
	UR 82–135	UR 190–216 & 1–27	UR 136–189	UR 28–81

Spatial Word Memory Task

The stimuli for the spatial working memory task were black dots located in one of eight pre-defined positions (up-up-right, up-right-right, right-right-down, right-down-down, left-down-down, left-left-down, left-left-up or up-up-left) on the screen equidistant from the centre of the monitor. The dot positions formed a virtual circle with a radius of 0.35 of the screen height. This layout was to ensure that participants did not engage in a verbal activity by verbalizing the locations, which might be the case with four basic locations (up, right, down, left). Also, the number of dot positions matched the number of letters used in the verbal working memory task.

Verbal Working Memory Task

The stimuli for the verbal working memory task included eight phonologically distinct letters (B, K, F, S, M, T, R, H), which were presented one per trial in the centre of the screen above the prime/target words. The letter position did not overlap with the prime/target position and the eye movement from the word stimulus to the working memory task stimulus was preserved. At the same time, the location of the letters was fixed across trials to prevent participants from engaging spatial working memory.

The stimuli for both the semantic relatedness and the working memory tasks were pseudorandomized using the pseudorandom list generator (van Heuven 2020). In the working memory tasks, the number of “same” or “different” responses appearing in a row was limited to three, and the number of “same” and “different” responses was equal. No more than four word pairs with the same degree of relatedness were presented in a row in the semantic relatedness task.

4.2.2.4. Procedure

The procedure was inspired by Heyman et al.’s (2015, 2017) studies but differed in several important ways. First, the working memory task and the semantic relatedness task in the current experiment were incorporated into one trial, whereas in Heyman et al. (2015, 2017) five lexical decision trials were embedded within one working memory task. The dual-task setting with interleaving working memory trials was used to maintain a constant working memory load throughout the experimental block and to prevent recency and primacy effects. Second, whereas the working memory task in Heyman et al. (2015, 2017) involved reproducing an easy or a complex dot pattern, the present experiment used dot and letter matching tasks to tax spatial and verbal working memory, respectively. The difficulty of the task depended on whether the current item was matched against the previous trial (1-back) or against two trials before (2-back). The n-back task requires participants to dynamically manipulate and update a set of items in the working memory. A similar dual-task approach involving n-back working memory tasks was used, for example, to investigate the effect of working memory load on reflexive saccade eye movements (Mitchell et al. 2002) and to explore the differential effects of spatial and verbal working memory load on the timing of the Simon effect (Clouter et al. 2015). In both studies, there were significant differences between different versions of the n-back task both in terms of performance on the working memory task itself and in terms of its influence on the primary executive tasks. In the present experiment, the n-back matching tasks ensured a consistent flow and a comparable procedure across verbal and spatial sessions.

Pre-experimental session

Before the actual experiment, participants familiarised themselves with information about the study, accepted an online consent form and completed a questionnaire with information about age, gender, native language, level of education, knowledge of foreign languages, and reading disorders. The information sheet, informed consent and questionnaire were prepared and administered using Microsoft Forms. After completing the questionnaire, participants received links to the first experimental session on the Pavlovia platform via email. The links to the second experimental session were emailed one week after the completion of the first session.

Semantic relatedness task

Each trial started with a semantic relatedness task. First, participants were shown a fixation cross for 500 ms, followed by a blank screen for 300 ms. Next, words in each word pair were presented one at a time. The first word of the word pair was presented in lowercase for 150 ms, followed by a blank screen for 50 ms. The next word of the word pair (target) then appeared in uppercase. Participants decided whether the target was semantically related to the lowercase word by pressing the “P” key for related or the “Q” key for unrelated. Participants were specifically instructed to decide for the “related” answer if in doubt. After 3,000 ms or after the participants’ response, whichever came sooner, the verbal or the spatial working memory task was presented depending on the session following a 500 ms blank screen. The intertrial interval was 500 ms.

Spatial working memory session

In the session with the spatial working memory task, participants were asked to decide whether the dot that they currently saw was in the same or different position as compared to the previous trial (low-load block) or to two trials before (high-load block). Participants were instructed to press the “P” key for same position and the “Q” key for different position. The dot remained on the screen until a response was provided, but no longer than 2,000 ms. The procedure of a trial with a spatial working memory task is presented in Fig. 14.

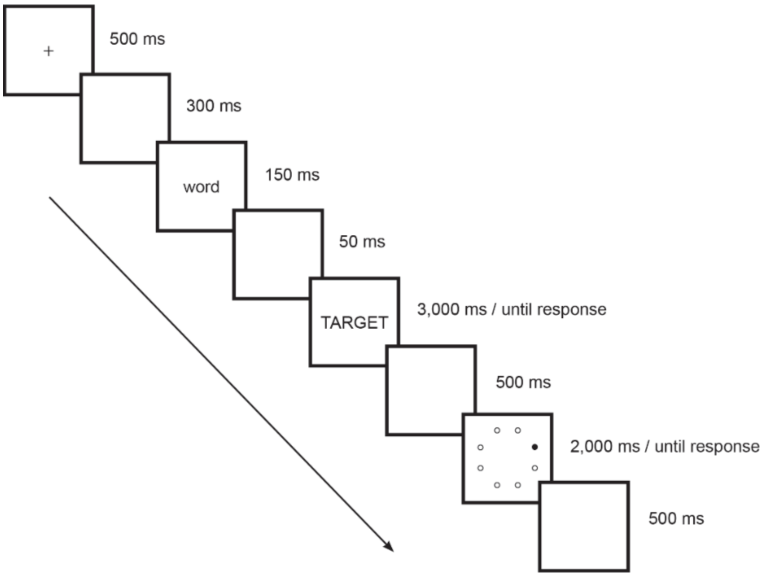

Fig. 14. Experimental procedure of a spatial working memory trial.

Verbal working memory session

In the session with the verbal working memory task, the task was to decide whether the letter that participants currently saw was the same or different as in the previous trial (low-load condition) or two trials before (high-load condition). Consistently with the spatial task, the letter remained on the screen until response, and maximum 2,000 ms. The procedure of a trial with a verbal working memory task is presented in Fig. 15.

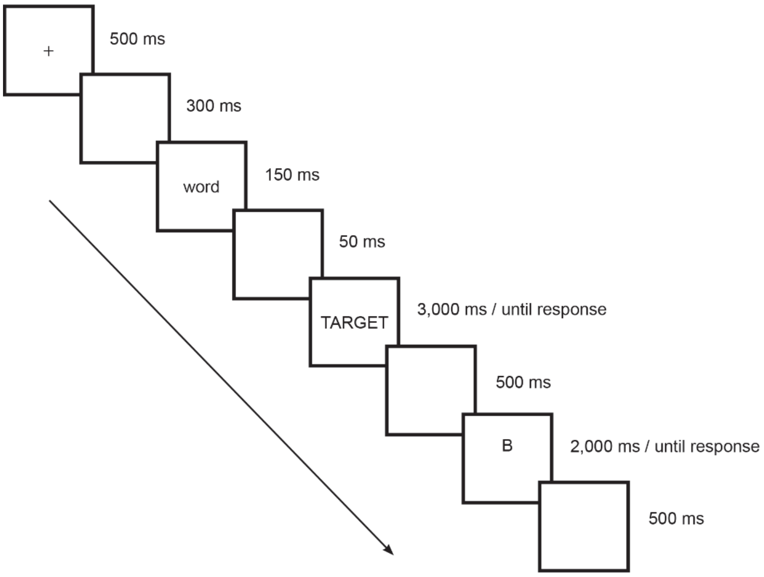

Fig. 15. Experimental procedure of a verbal working memory trial.

There were two self-paced breaks within each block. After each break, two filler items were presented before the new set of items. Participants were instructed to press "Q" for the first two items in the working memory task, and responses to these items were excluded from analysis.

At the beginning of each session, participants went through a practice session in order to get familiar with the dual task. The practice included three parts: only the semantic relatedness task, only the working memory task, and both tasks combined. Throughout the practice session, participants received immediate feedback whether their answer was correct, incorrect, or too slow. A threshold result of 80% of correct responses in the third part of the practice session was required for participants to move forward to the experimental session. The overall average duration of each block was 20 minutes. The procedure and exact timing were piloted with five participants, whose results were not included in the analysis.

4.2.3. Results

The analysis of response times was performed after removing incorrect responses and outliers. Outliers were removed based on a cut-off value of 2 standard deviations from the mean for each participant and target word in each condition. In addition, fast responses

(< 250 ms) were removed. In total 1.37% of responses as well as filler items from either task were excluded from analysis.

The data were analysed using generalised linear mixed-effects models (GLMM) in R version 4.1.1 (R Core Team, 2021) with the lme4 package version 1.1.27.1 (Bates et al. 2015). Generalised linear models were used because they do not require the assumption that RTs are normally distributed, thus making it possible to analyse untransformed RT data and investigate interaction effects more reliably (Lo and Andrews 2015; Lupker et al. 2020).

4.2.3.1. Working memory tasks

Fixed effects in the GLM model included Load (low vs high), Task (spatial vs verbal) and their interaction. Both factors were coded using sum coding (-.5 vs .5). Because models with random slopes failed to converge, the final model included only random intercepts for subjects and items.

Final model: `glmer(rt ~ task * load + (1|subject) + (1|item), data = WM.data, family = Gamma(link="identity")).`

The output of the GLMM analysis of response times is presented in Table 12. Participants were significantly slower ($p < 0.001$) in the 2-back task as compared to the 1-back version regardless of the type of working memory involved. Responses in the verbal task were slower ($p < 0.001$) than in the spatial task. The interaction between Task and Load was also significant ($p < 0.001$). Bonferroni-corrected pairwise comparisons obtained using the emmeans package (Lenth 2021) revealed a significant difference between verbal and spatial tasks in both load conditions (16 ms, $p < .001$ for low load vs 59 ms, $p < .001$ for high load).

Table 12. GLMM output for the RT analysis in the working memory tasks (spatial vs verbal task, low vs high load) in Experiment 2.1.

Factors	*b*-value	SE	*t*-value	*p*-value
Task	37.175	1.476	25.19	< 0.001
Load	184.365	1.544	119.43	< 0.001
Task * Load	43.107	1.657	26.02	< 0.001

For error analysis, the binomial family was used in the GLM model and the BOBYQA optimizer was applied because the model with the default optimizer failed to converge. Fixed and random factors in the model were the same as for the RT analysis.

Final model: `glmer(corr ~ task * load + (1|subject) + (1|item), data = WM.data.all, family = binomial, control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 1e6)))`.

The output of the GLMM analysis of error rates is presented in Table 13. Participants made more errors ($p < 0.001$) in the 2-back task as compared to the 1-back version regardless of the type of working memory involved. Error rates in the verbal task were significantly higher ($p < 0.001$) than in the spatial task. The interaction between Task and Load was also significant ($p = 0.02$). Bonferroni-corrected pairwise comparisons revealed a significant difference between verbal and spatial tasks only in the high-load condition (0.4%, $p = 0.25$ for low load vs 3.8%, $p < .001$ for high load). Mean response times and error rates are presented in Table 14.

Table 13. GLMM output for the error analysis in the working memory tasks (spatial vs verbal task, low vs high load) in Experiment 2.1.

Factors	*b*-value	SE	*z*-value	*p*-value
Task	-0.11526	0.02652	-4.347	< 0.001
Load	-1.10370	0.05309	-20.790	< 0.001
Task * Load	-0.12821	0.05304	-2.417	0.02

Table 14. Mean response times (in ms) and error rates (in %) in the working memory task (Experiment 2.1) as a function of task and load. Values in parentheses indicate standard errors.

Load	Variable	Spatial task	Verbal task
Low load	RT	676 (2.7)	692 (2.57)
	Error rate	4.3 (0.26)	4.7 (0.28)
High load	RT	839 (2.73)	898 (2.98)
	Error rate	10.5 (0.4)	14.3 (0.47)

4.2.3.2. Semantic relatedness task

RT analyses

Fixed effects in the model included Load (low vs high), Task (spatial vs verbal), Relatedness (SR vs WR vs UR), and their interactions. The factors Load and Task were coded using sum coding (-.5 vs .5), whereas Relatedness was coded using deviation coding with the unrelated condition as the baseline. The random structure included only random intercepts for subjects and items because models with random slopes failed to converge. The final model with the default optimizer failed to converge, therefore the BOBYQA optimizer was used. RT means and standard errors are summarised in Table 15.

Final model: `glmer(rt ~ task * load * relatedness + (1|subject) + (1|item), data = SRT.data, family = Gamma(link="identity"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun=1e6)))`.

Table 15. Mean response times (in ms) in the semantic relatedness task (Experiment 2.1) as a function of working memory task, working memory load and word-pair relatedness. Values in parentheses indicate standard errors.

	Spatial task		Verbal task	
	Low load	High load	Low load	High load
Strongly related	813 (3.76)	885 (4.77)	834 (3.83)	913 (5.08)
Weakly related	919 (3.05)	989 (3.08)	930 (3.41)	1036 (3.64)
Unrelated	870 (3.97)	938 (2.93)	867 (3.42)	944 (3.03)

Table 16. GLMM output for the RT analysis in the semantic relatedness task (Experiment 2.1).

Factors	*b*-value	SE	*t*-value	*p*-value
Task	18.505	1.708	10.833	< 0.001
Load	79.012	2.244	35.204	< 0.001
Relatedness (WR vs UR)	63.574	2.089	30.439	< 0.001
Relatedness (SR vs UR)	-43.748	2.552	-17.142	< 0.001
Task * Load	17.783	2.271	7.829	< 0.001
Task * Relatedness (WR vs UR)	27.766	2.487	11.163	< 0.001
Task * Relatedness (SR vs UR)	23.4	2.451	9.547	< 0.001
Load * Relatedness (WR vs UR)	14.528	2.047	7.096	< 0.001
Load * Relatedness (SR vs UR)	2.835	3.668	0.773	0.44
Task * Load * Relatedness (WR vs UR)	27.6	1.917	14.398	< 0.001

Task * Load * Relatedness (SR vs UR)	-1.206	2.198	-0.549	0.58

Note. SR – strongly related pairs, WR – weakly related pairs, UR – unrelated pairs.

The final model output is presented in Table 16. The analysis revealed significant main effects of Task, Load, and Relatedness (*p*'s < 0.001). There was a 44 ms facilitation effect for strongly related pairs, i.e. participants were overall faster at judging strongly related pairs relative to unrelated ones. For weakly related pairs, in contrast, there was a 64 ms inhibition effect, i.e. responses to weakly related pairs were slower than to unrelated ones. Furthermore, participants were 19 ms slower in the semantic relatedness task when it was interleaved with the verbal than the spatial working memory task. Responses in the high-load condition were overall 79 ms slower than in the low-load condition. There was an interaction between Load and Task that revealed a larger effect of load in the verbal than spatial working memory task (88 ms vs 70 ms, $p < 0.001$). Furthermore, there were interactions between Task and Relatedness for strongly related vs unrelated pairs showing a smaller facilitation effect with the verbal than with the spatial working memory task (32 ms vs 55 ms, $p < 0.001$), and for weakly related vs unrelated pairs showing a larger inhibition effect with the verbal than with the spatial working memory task (-78 ms vs -50 ms, $p < 0.001$). The interaction between Relatedness and Load was only significant for weakly related pairs and revealed that the inhibition effect was larger with the high-load than low-load working memory task (71 ms vs 56 ms, $p < 0.001$). This two-way interaction was not significant for strongly related pairs ($p = 0.44$). Crucially, there was a three-way interaction between Task, Load and Relatedness for weakly related pairs ($t = 14.4$, $p < 0.001$) but not for strongly related pairs ($t = -0.55$, $p = 0.58$). As can be seen in Fig. 16 and in Table 17, load did not impact weakly related pairs with the spatial working memory task (50 ms vs 49 ms, $p = 0.76$), whereas with the verbal task a high memory load resulted in a stronger inhibition effect than a low memory load (92 ms vs 63 ms, $p < .001$).

Table 17. Reaction time differences (in ms) of weakly related (WR) and strongly related (SR) pairs relative to unrelated pairs (UR) as a function of working memory task and load. Values in parentheses indicate standard errors.

	Spatial task		Verbal task	
	Low load	High load	Low load	High load
WR vs UR	49 (2.81)	50 (2.57)	63 (2.29)	92 (3)
SR vs UR	-57 (2.91)	-54 (3.74)	-33 (2.61)	-31 (4.18)

Note. All differences are significant with *p* < .001. Negative values indicate inhibition (slower responses relative to unrelated).

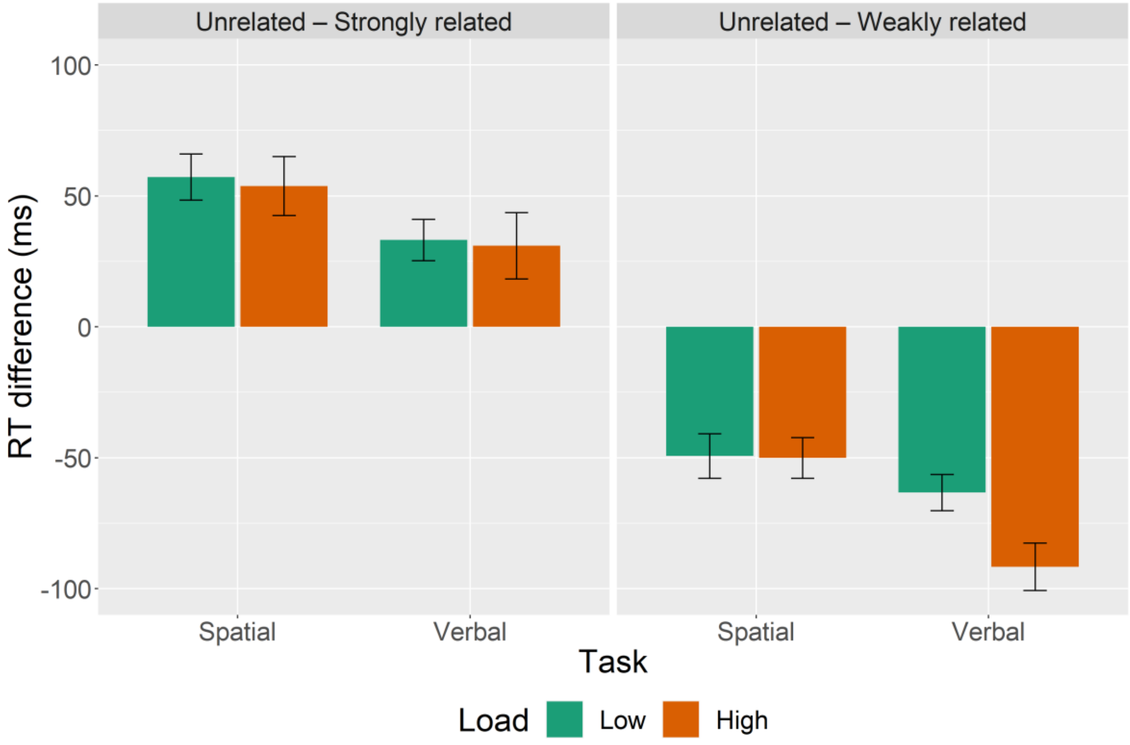

Fig. 16. RT differences for strongly related and weakly related pairs relative to unrelated pairs as a function of type of working memory task and load. Positive values indicate facilitation, whereas negative values indicate inhibition relative to unrelated pairs. Error bars indicate 95% confidence intervals.

Error analyses

Similarly to the working memory task, the binomial family was used in the GLM model for error analysis and the BOBYQA optimizer was applied because the model with the default optimizer failed to converge. Fixed and random factors in the model were the same as for the RT analysis.

Final model: `glmer(corr ~ task * load * relatedness + (1|subject) + (1|item), data = SRT.data.all, family = binomial, control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun=1e6)).`

Error rate means and standard errors are summarised in Table 18, and the output of the GLMM analysis is presented in Table 19. There were main effects of Load and Task (p's < 0.001) with more errors observed when SRT was interleaved with the 2-back working memory task relative to the 1-back one and with the verbal working memory task relative to the spatial one. More errors were found for RR and SR pairs relative to UR ones (p's < 0.001). The interactions between Load and Relatedness and between Task and Relatedness were significant for both RR pairs (p's < 0.001) and SR pairs ($p < 0.001$ and $p < 0.01$, respectively). The interaction between Task and Load and the three-way interaction between Task, Load and Relatedness were not significant (p's > 0.3).

Table 18. Mean error rates (in %) in the semantic relatedness task (Experiment 2.1) as a function of working memory task, working memory load and word-pair relatedness. Values in parentheses indicate standard errors.

	Spatial task		Verbal task	
	Low load	High load	Low load	High load
Strongly related	7.3 (0.64)	7.2 (0.64)	8.1 (0.67)	9.5 (0.73)
Weakly related	28.4 (1.11)	30.6 (1.13)	29.3 (1.12)	32.6 (1.15)
Unrelated	0.6 (0.13)	2.1 (0.25)	1.0 (0.18)	4.4 (0.36)

Table 19. GLMM output for the error analysis in the semantic relatedness task (Experiment 2.1).

Factors	*b*-value	SE	*z*-value	*p*-value
Task	-0.32680	0.06538	-4.998	< 0.001
Load	-0.55838	0.06539	-8.539	< 0.001
Relatedness (WR vs UR)	-3.54600	0.08743	-40.558	< 0.001
Relatedness (SR vs UR)	-1.77781	0.09397	-18.919	< 0.001
Task * Load	-0.12444	0.13077	-0.952	0.34
Task * Relatedness (WR vs UR)	0.67013	0.17285	3.877	< 0.001
Task * Relatedness (SR vs UR)	0.52702	0.18801	2.803	< 0.01
Load * Relatedness (WR vs UR)	1.29235	0.17257	7.489	< 0.001
Load * Relatedness (SR vs UR)	1.35852	0.18772	7.237	< 0.001
Task * Load * Relatedness (WR vs UR)	0.06880	0.34501	0.199	0.84
Task * Load * Relatedness (SR vs UR)	-0.07055	0.37520	-0.188	0.85

Note. SR – strongly related pairs, WR – weakly related pairs, UR – unrelated pairs.

RT distribution analysis

To further explore the effects of working memory task and load on relatedness judgements of pairs with different degrees of relatedness, response times were compared in a distributional analysis based on Perea et al. (2018). The mean response times in the semantic relatedness task were calculated across five quantiles (.1, .3, …, .9) for each level of load in the concurrent spatial and verbal working memory task. Delta plots (see Fig. 17) were used to illustrate RT distributions across quantiles depending on experimental conditions. Delta plots are useful to observe the time dynamics of responses and compare the effect of manipulation for slower and faster responses (De Jong et al. 1994; Schwarz and Miller 2012).

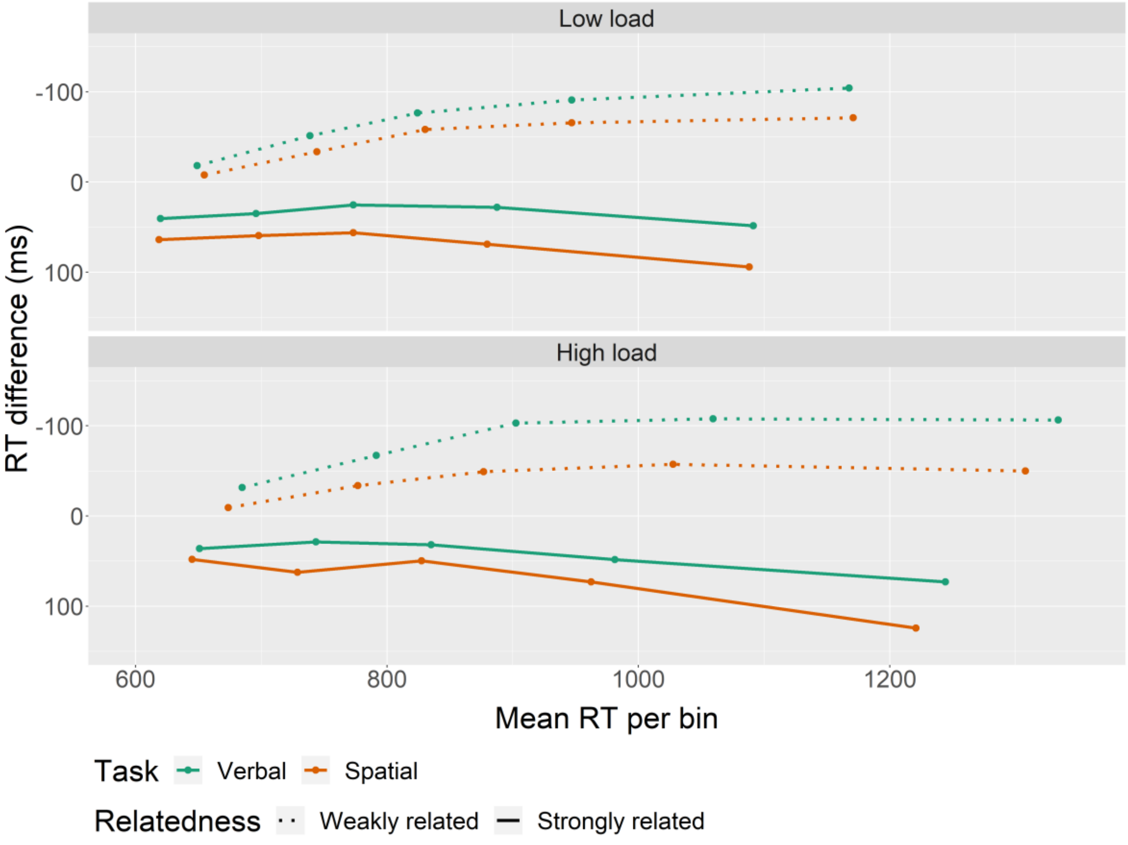

Fig. 17. Differences between reaction times to unrelated and related words in Experiment 2.1 as a function of quantile (.1, .3, …, .9), working memory load, working memory task and relatedness.

Fig. 17 shows differences (deltas) between response times to targets preceded by unrelated primes relative to weakly related (dotted lines) and strongly related (solid lines) primes. Positive values on the y-axis indicate a facilitation effect, i.e. faster responses to related than to unrelated targets, while negative values indicate an inhibition effect, i.e.

slower responses to related than to unrelated targets. The values on the x-axis show mean RTs for each of the five quantiles depicted as solid circles. It should be noted, however, that the delta plots are based on raw response times, while the values reported in the RT analyses section above are marginal means obtained from the generalised mixed-effects model.

Overall, the delta plots illustrate that the effects found in the main analysis are stable across the entire distribution. Consistently negative values for weakly related pairs suggest an inhibition effect, whereas strongly related pairs demonstrate a facilitation effect in all working memory conditions. The pattern of the two-way interaction between task and relatedness is also visible for both load conditions: the inhibition effect for weakly related pairs is consistently larger, while the facilitation effect for strongly related pairs is consistently smaller when verbal working memory (green lines) is engaged as compared to spatial working memory (orange lines). Whereas the difference between verbal and spatial tasks is similar between low-load and high-load conditions for closely related pairs, for weakly related pairs it is noticeably larger in the high-load condition, which illustrates the significant three-way interaction found in the GLMM analysis.

4.2.4. Discussion

The aim of Experiment 2.1 was to investigate the effect of spatial and verbal working memory load on semantic relatedness judgements with semantically strongly and weakly related word pairs. The results revealed that the type of the working memory task impacts relatedness judgements of strongly and weakly related pairs differently. With the verbal working memory task, the facilitation effect for strongly related pairs was weaker than with the spatial working memory task, whereas the inhibition effect for weakly related pairs was larger with the verbal working memory task than with the spatial working memory task. Semantically weakly related pairs were particularly sensitive to additional working memory demands because high working memory load as opposed to low load enhanced the inhibition effect for weakly related but did not change the pattern of the facilitation effect for strongly related pairs. The results will be further discussed in the General Discussion chapter of this thesis (Chapter 6). Overall, these findings suggest that, in line with some previous research (Neely 1991; Neely and Kahan 2001; Hutchison et al. 2014; Heyman et al. 2015; Radel et al. 2015), semantic processing can be affected by high-order executive functions. Furthermore, the results corroborate the domain-specific account of working memory (Baddeley and Hitch 1974; Shah and Miyake 1996; Nagel et al. 2007; Baddeley 2011; Baddeley et al. 2020).

One of the findings of Experiment 2.1 was that weakly related pairs were judged significantly slower than unrelated pairs in all working memory conditions. This inhibition effect was consistent with the results of Kuperberg et al.'s (2008) semantic relatedness experiment but different from the facilitation effect found in the primed lexical decision task (Kuperberg et al. 2008; Rataj et al. 2023). The inhibition effect was also inconsistent with Ortu et al. (2013), who used a delayed response in the semantic relatedness task and found a facilitation effect for moderately associated pairs. To investigate the pattern of relatedness judgements in the absence of concurrent working memory task, Experiment 2.2 described in the following section used the same procedure as in Experiment 2.1 but included only the semantic relatedness task. The impact of procedure without working memory load was investigated in Experiment 2.3 presented in Section 4.4.

4.3. Relatedness judgements without working memory load (Experiment 2.2)

4.3.1. Aims, research questions and hypotheses

Experiment 2.2 served as a control for Experiment 2.1 and involved only the semantic relatedness task without the working memory task. Its main aim was to establish the pattern of relatedness judgements of strongly related, weakly related and unrelated Polish word pairs without any additional working memory manipulations. The research question addressed in this experiment concerned the influence of the strength of semantic relatedness on relatedness judgements.

The results of Experiment 2.1 revealed an inhibition effect for weakly related pairs in the semantic relatedness task regardless of the concurrent working memory task or load. The stimuli that were used in Experiment 2.1 were also tested in a semantic priming lexical decision task (Rataj et al. 2023). Rataj et al. found a graded effect of relatedness, i.e. target words with strongly related primes evoked the shortest RTs, unrelated primes the longest RTs, and the RTs for weakly related primes fell in-between. If the present experiment reveals a facilitation effect for weakly related pairs, consistent with Rataj et al. (2023), it will suggest that additional working memory load reverses the pattern of results for prime-target pairs with weaker semantic links. If, however, the present experiment confirms the inhibitory effect found in Experiment 2.1, it will suggest that either the procedural differences play a role in the pattern of results, or that the additional inhibitory task has an effect on the processing of weakly related pairs in a semantic judgement task.

4.3.2. Method

4.3.2.1. Participants

54 students of the Faculty of English and the Institute of Russian and Ukrainian Philology of Adam Mickiewicz University in Poznan (37 women, 5 preferred not to state, M_{age} = 21.5 years, SD_{age} = 1.9 years) took part in the experiment. They received course credits in return for their participation. Two participants were not native speakers of Polish and were excluded from analysis. Further, data from six participants who had an accuracy of less than 80% for unrelated and strongly related pairs were excluded from analysis, which resulted in a final sample of 46 participants.

4.3.2.2. Design, materials, and procedure

Both the design, lexical materials, and the experimental procedure were the same as in Experiment 2.1 except that the working memory task was removed. Because the experiment included only one session, stimuli for the semantic relatedness task were divided into four lists so that each participant saw all 216 targets words preceded by primes with a different degree of relatedness. Each list contained 54 strongly related, 54 weakly related, and 108 unrelated prime-target pairs. The same pseudorandomisation procedure was applied as in Experiment 2.1. The average duration of the experimental session was 15 minutes.

4.3.3. Results

The data pre-processing and statistical analyses were identical to Experiment 2.1. Outliers accounted for a total of 1.92% of responses and were excluded from the analysis. The only fixed effect in the generalized linear mixed-effect model was Relatedness (UR vs SR vs WR). It was coded using deviation coding with the unrelated condition as the baseline.

Final model for the RT analysis: `glmer(rt ~ relatedness + (1|subject) + (1|item), data = SRT.data, family = Gamma(link="identity")).`

The model for the error analysis failed to converge with the default optimizer, so the BOBYQA optimizer was applied. Final model for the error analysis: `glmer(corr ~ relatedness + (1|subject) + (1|item), data = SRT.data.all, family = binomial, control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 1e6))).`

RT means and standard errors are summarised in Table 20 and the final model output is presented in Table 21 for the RT analysis and in Table 22 for the error analysis. The results demonstrate a significant facilitation effect for strongly related pairs and a significant inhibition effect for weakly related pairs (*p*'s < 0.001). Thus, participants were 71 ms faster at recognizing target words that were preceded by a strongly related prime word, but 26 ms slower when targets were preceded by a weakly related prime as compared to an unrelated word. Participants also made significantly more errors in their responses to both strongly related and weakly related pairs (*p*'s < 0.001).

Table 20. Mean response times and error rates as a function of word-pair relatedness (Experiment 2.2). Values in parentheses indicate standard errors.

Relatedness	Response time (ms)	Error rate (%)
Strongly related	828 (4.81)	4.9 (0.44)
Weakly related	925 (5.20)	26.6 (0.89)
Unrelated	899 (4.49)	1.7 (0.18)

Table 21. GLMM output for the RT analysis (Experiment 2.2).

Factors	*b*-value	SE	*t*-value	*p*-value
Relatedness (WR vs UR)	26.314	3.453	7.621	< 0.001
Relatedness (SR vs UR)	-71.413	2.862	-24.953	< 0.001

Note. SR – strongly related pairs, WR – weakly related pairs, UR – unrelated pairs.

Table 22. GLMM output for the error analysis (Experiment 2.2).

Factors	*b*-value	SE	*z*-value	*p*-value
Relatedness (WR vs UR)	-3.24790	0.12270	-26.471	< 0.001
Relatedness (SR vs UR)	-1.13109	0.14536	-7.781	< 0.001

Note. SR – strongly related pairs, WR – weakly related pairs, UR – unrelated pairs.

A distributional analysis of reaction times depending on the relatedness condition was performed similar to Experiment 2.1. The delta plot (Fig. 18) illustrates a consistent inhibition effect for weakly related pairs and a facilitation effect for strongly related pairs throughout the RT distribution.

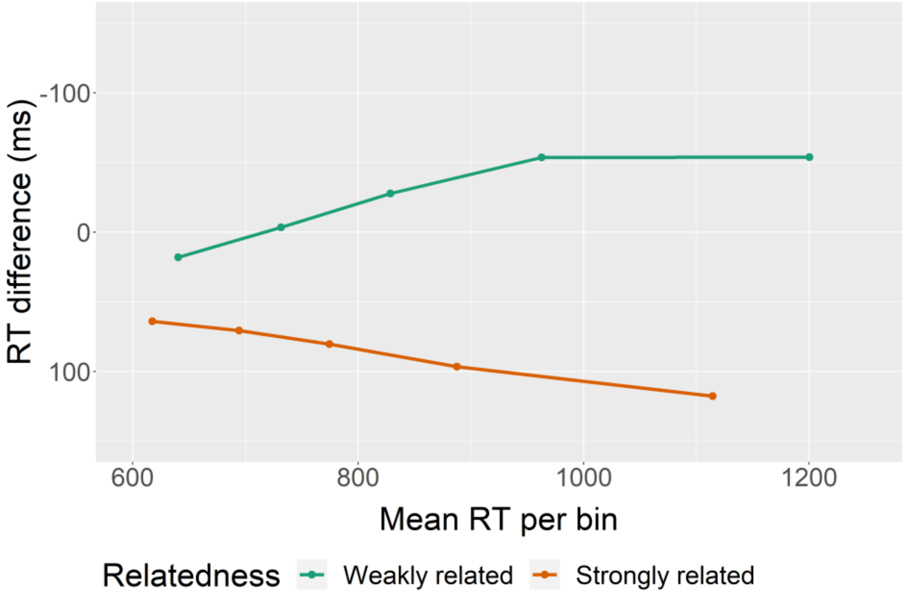

Fig. 18. Differences between reaction times to unrelated and related words in Experiment 2.2 as a function of quantile (.1, .3, …, .9) and relatedness.

4.3.4. Discussion

The main finding of this control experiment was that it reproduced the effect of the degree of semantic relatedness on relatedness judgements found in Experiment 2.1 that also involved a concurrent working memory task. Semantically weakly related pairs were judged significantly slower than unrelated pairs, whereas a facilitation effect was found for semantically strongly related pairs. These results suggest that semantic processing can be modulated by the strength of semantic relations also in the absence of additional working memory load. The analysis of previous studies (Kuperberg et al. 2008; Ortu et al. 2013; Rataj et al. 2023) suggests that the procedure may have an effect on relatedness judgements. This assumption was tested in Experiment 2.3 presented in the following section by introducing a delay between the target presentation and response in the semantic relatedness task.

4.4. Relatedness judgements with delayed decisions (Experiment 2.3)

4.4.1. Aims, research questions, hypotheses

Two previous experiments conducted within the present study revealed significantly slower responses to weakly related word pairs as compared to unrelated ones. This inhibition effect for pairs with weaker semantic links is in line with what Kuperberg et al. (2008) found in their study, which used words with three levels of semantic relatedness and investigated the influence of task and semantic relationship on semantic processing. However, this pattern is different from what was reported in Ortu et al. (2013) who investigated whether the level of semantic relatedness has an impact on neurophysiological parameters of semantic processing. Based on the analysis of the above studies, the discrepancy between the studies may be due to a procedural difference of the semantic relatedness task. In Ortu et al.’s (2013), participants made a relatedness decision when they saw a question mark on the screen that followed the target word after a short delay. A similar procedure was used in Rataj et al. (in preparation), who investigated in an event-related potential (ERP) study the effect of executive demands on relatedness judgements.

This delay was needed to prevent response-related EEG activity from contaminating the signal. In Kuperberg et al. (2008), as well as in Experiments 2.1 and 2.2 of the present study, however, the research method did not require the delay between target presentation and the relatedness judgements, so participants could make a decision immediately after the target word was presented.

Based on the previous findings, the interval between target presentation and decision making in a semantic relatedness task may influence the pattern of responses to weakly related pairs. The present control study aimed to verify this assumption by modifying the procedure of a previously conducted experiment involving a semantic relatedness task. The change in procedure was hypothesised to result in a pattern of results similar to Ortu et al. (2013) and Rataj et al. (2023), i.e. slowest response times to unrelated pairs, faster response times to weakly related pairs, and the fastest response times to strongly related pairs (see Fig. 3 in Section 1.2.3).

4.4.2. Method

4.4.2.1. Participants

46 students of the Faculty of English and the Institute of Russian and Ukrainian Philology of Adam Mickiewicz University in Poznan (38 women, 3 preferred not to state, M_{age} = 20.8 years, SD_{age} = 1.7 years) took part in the experiment. They received course credits in return for their participation. Data from one participant with an accuracy of less than 80% for unrelated and strongly related pairs were excluded from analysis, which resulted in a final sample of 45 participants.

4.4.2.2. Design, materials and procedure

The design and materials were the same as in Experiment 2.2. The only difference was in the task procedure, which was modified to be identical to Rataj et al. (in preparation). The trial of the present experiment is presented in Fig. 19. First, participants were shown a fixation cross for 500 ms, followed by a blank screen for 50 ms. Next, a lowercase word (prime) was presented for 150 ms, followed by a blank screen for 50 ms. The uppercase target word then appeared for 1,000 ms, followed by a blank screen for 50 ms. Then, participants saw a trigger question "ZWIĄZANE?" ("RELATED?") and their task was to decide whether the target word was semantically related to the prime word by pressing the 'P' key for related or the 'Q' key for unrelated. The question remained on the screen for 2,000 ms or until the response. The intertrial interval was 500 ms. The experiment was approved by the Ethics Committee for Research Involving Human Participants at the Adam Mickiewicz University in Poznań (Resolution 1/2021/2022).

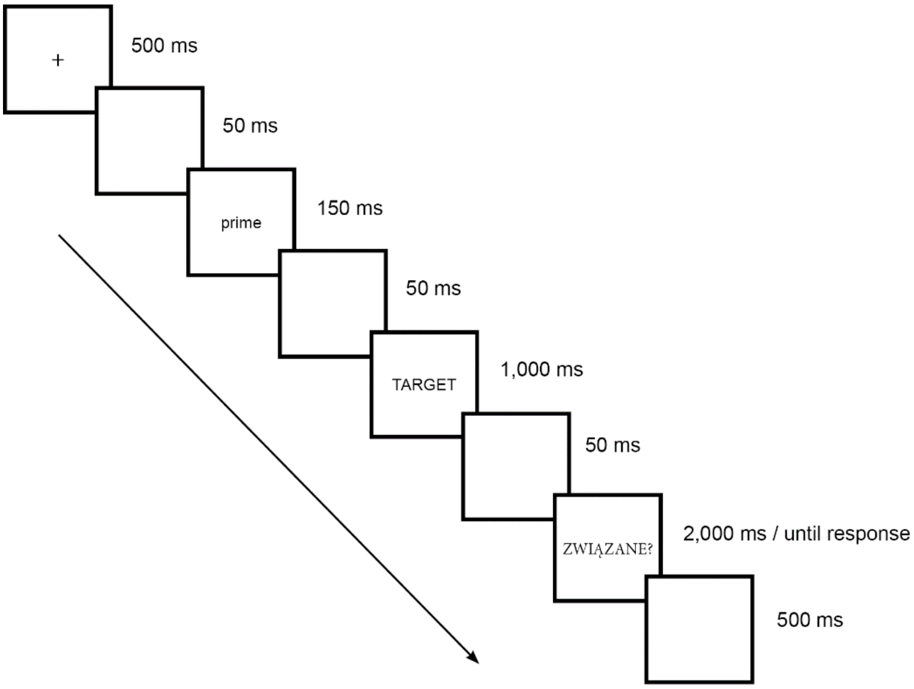

Fig. 19. The trial flow of Experiment 2.3.

Thus, longer presentation time of the target word and the additional screen with the trigger question that introduced a delay between the target word and the relatedness judgement was what distinguished the present experiment from Experiment 2.2. Instructions for participants were modified accordingly to emphasise that responses should only be given once the trigger question appears on the screen. Similar to the previous experiments, participants first conducted a practice session, in which early responses, i.e.

responses provided while the target word was still presented, were flagged and counted as errors.

4.4.3. Results

The same approach to removing outliers and pre-processing the data was followed as in Experiments 2.1 and 2.2. However, responses faster than 250 ms were not considered outliers because participants could anticipate the timing of the trigger question and provide very quick responses. In total, 2.14% of responses were excluded from the analysis.

RT means and standard errors are summarised in Table 23 and the final model output is presented in Table 24 for the RT analysis and in Table 25 for the error analysis. Participants showed a significant 32 ms facilitation effect ($p < 0.001$) when target words were preceded by a strongly related prime word, but a 30 ms inhibition effect ($p < 0.001$) when targets were preceded by a weakly related prime as compared to an unrelated word. There were also significantly more errors in responses to both strongly related and weakly related pairs as compared to unrelated ones (p's < 0.001).

Table 23. Mean response times and error rates as a function of word-pair relatedness (Experiment 2.3). Values in parentheses indicate standard errors.

Relatedness	Response time (ms)	Error rate (%)
Strongly related	420 (4.79)	4.8 (0.44)
Weakly related	482 (4.62)	25.3 (0.89)
Unrelated	452 (4.42)	1.4 (0.17)

Table 24. GLMM output for the RT analysis (Experiment 2.3).

Factors	*b*-value	SE	*t*-value	*p*-value
Relatedness (WR vs UR)	30.284	2.803	10.80	< 0.001
Relatedness (SR vs UR)	-31.753	2.622	-12.11	< 0.001

Note. SR – strongly related pairs, WR – weakly related pairs, UR – unrelated pairs.

Table 25. GLMM output for the error analysis (Experiment 2.3).

Factors	*b*-value	SE	*z*-value	*p*-value
Relatedness (WR vs UR)	-3.5852	0.1391	-25.768	< 0.001
Relatedness (SR vs UR)	-1.3624	0.1578	-8.833	< 0.001

Note. SR – strongly related pairs, WR – weakly related pairs, UR – unrelated pairs.

The distributional analysis (see Fig. 20) indicated that the inhibition effect for weakly related pairs and the facilitation effect for strongly related pairs are stable throughout the RT distribution and become even more pronounced for slower responses.

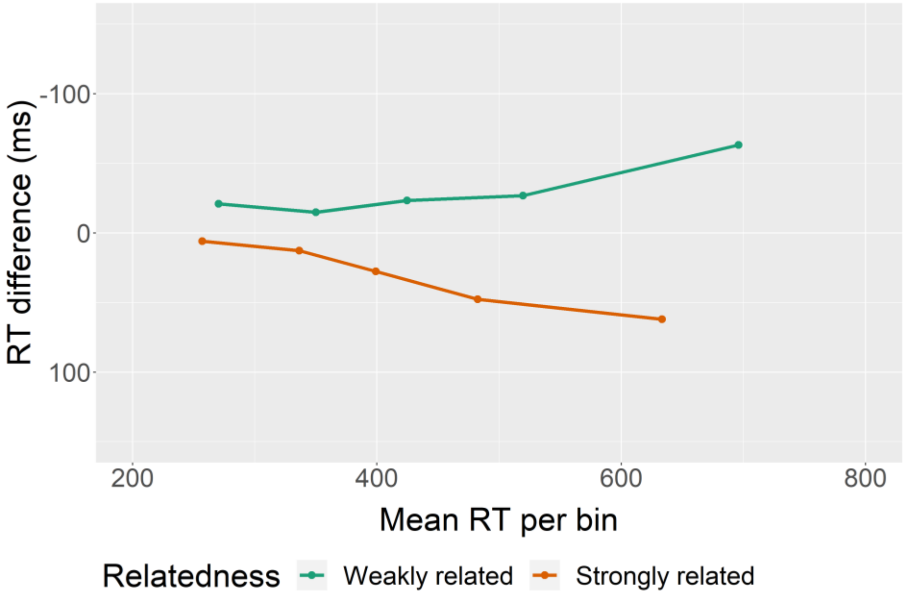

Fig. 20. Differences between reaction times to unrelated and related words as a function of quantile (.1, .3, …, .9), working memory load, working memory task and relatedness.

4.4.4. Discussion

The results of this control experiment demonstrated that the inhibition effect for semantically weakly related pairs and the facilitation effect for semantically strongly related pairs compared to unrelated pairs was consistently observed in the semantic relatedness task also when there was a delay between the presentation of the target and the relatedness judgement. These results replicate the pattern of relatedness judgements found in experiments with immediate judgements that were made under additional working memory load (Experiment 2.1) or without it (Experiment 2.2). The following section presents a combined analysis of results from Experiments 2.2 and 2.3 followed by a brief discussion of all three experiments of Study 2.

4.5. Combined results of Experiments 2.2 and 2.3

Fig. 21 shows RTs to word pairs with different degrees of relatedness in Experiment 2.2, in which participants made an immediate relatedness judgement in response to the target word while it was still visible on the screen, and in Experiment 2.3, in which participants gave a delayed response after the target word disappeared and a trigger question appeared on the screen. Expectedly, the overall RTs were faster in Experiment 2.3; however, it is seen from the figure that the pattern of results is similar across the experiments with the fastest responses to strongly related pairs, slower responses to unrelated pairs, and the slowest responses to weakly related pairs.

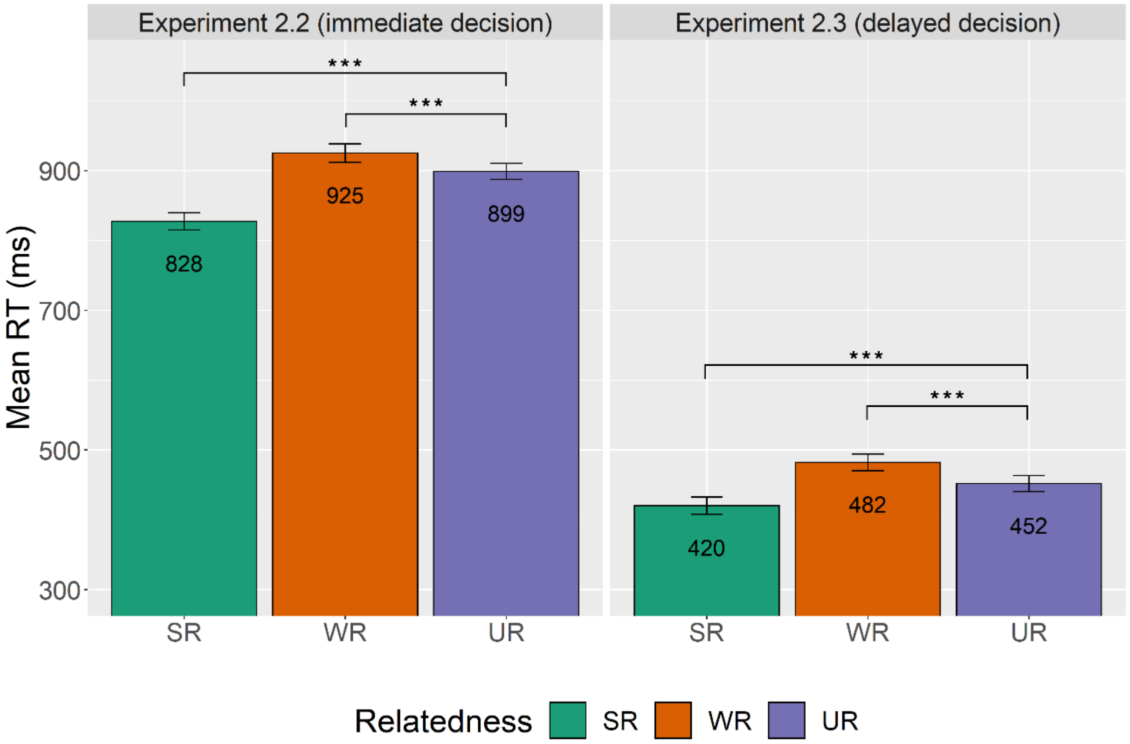

Fig. 21. Mean RTs for strongly related (SR), weakly related (WR) and unrelated (UR) pairs in Experiments 2.2 and 2.3. Error bars indicate 95% confidence intervals. *** $p < 0.001$.

Although the direction of inhibition and facilitation effects was consistent regardless of the experimental procedure, the size of the facilitation effect was different. It is demonstrated in Fig. 22 that the facilitation effect for strongly related pairs was more than twice as large in Experiment 2.2 with the immediate decision than in Experiment 2.3 with the delayed decision (71 ms vs 32 ms). The inhibition effect, on the contrary, was similar in both experiments (30 ms vs 26 ms).

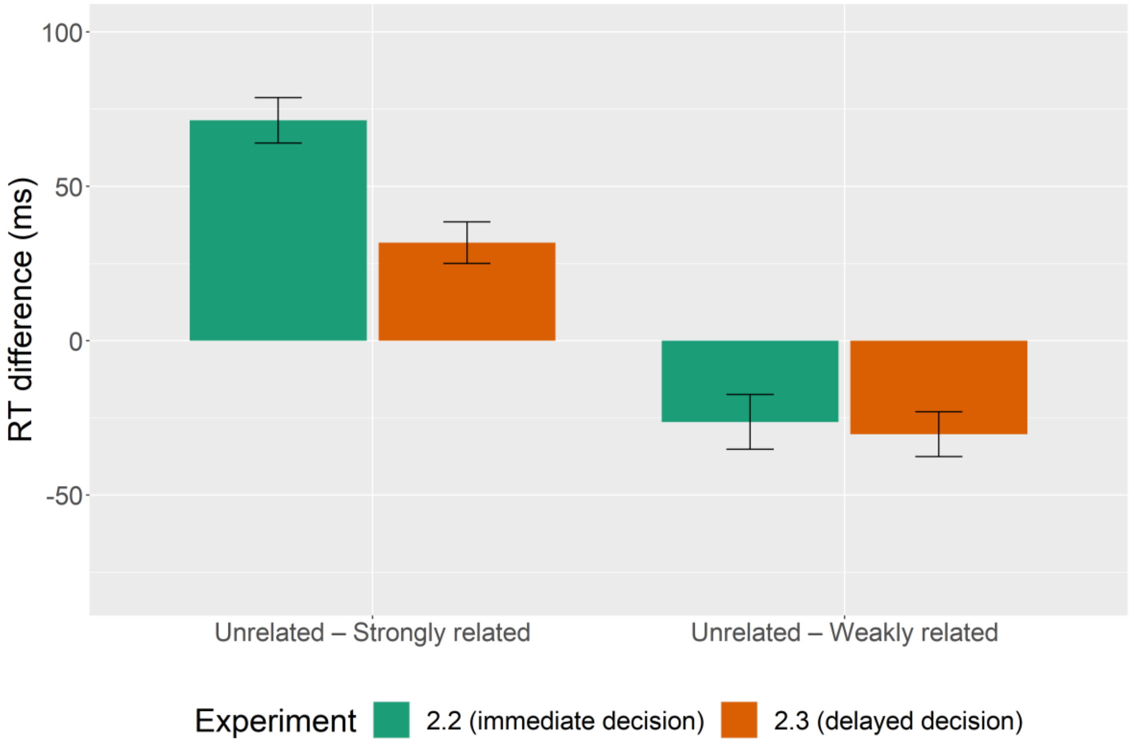

Fig. 22. RT differences for strongly related and weakly related pairs relative to unrelated pairs in Experiments 2.2 and 2.3. Positive values indicate facilitation, whereas negative values indicate inhibition relative to unrelated pairs. Error bars indicate 95% confidence intervals.

4.6. General discussion

The present study has several crucial findings regarding the influence of working memory on semantic relatedness judgements. Firstly, it provides evidence that semantic processing is affected by the type of the secondary working memory task. An additional task requiring verbal working memory resources was shown to interfere with semantic processing in a relatedness judgement task. Such interference reduces the facilitatory effect for strongly related pairs but results in an increased inhibitory effect for weakly related pairs as compared to the spatial working memory task. Secondly, the extent of the working memory load only affected relatedness judgements for weakly related pairs in the verbal working memory condition. High verbal working memory load resulted in increased inhibition as compared to low verbal working memory load, an effect not observed in the spatial task or for strongly related pairs. Thirdly, participants were consistently slower and less accurate at judging weakly related pairs as compared to unrelated or strongly related pairs regardless of the additional working memory task. Surprisingly, slower responses for weakly related pairs as compared to unrelated pairs were also observed in both control experiments even when no additional working memory load was involved (Experiment 2.2) and when the relatedness decisions were made after a delay (Experiment 2.3). This inhibition effect for weakly related pairs suggests that different mechanisms are involved in the semantic processing of words with different degree of semantic relatedness. The findings of this study will be discussed in detail in Chapter 6.

4.7. Conclusions

To summarise, the findings of this study indicate that semantic processing is dependent on the degree of semantic relatedness between words and that semantic relatedness judgements can be modulated by concurrent working memory load, with verbal working memory having a stronger effect relative to spatial working memory. Additionally, Study 2 demonstrated that the semantic relatedness task is an effective method for investigate semantic processing and can be particularly suitable for capturing the effects of working memory on language processing. Study 3 presented in the following chapter also used this task to investigate the relatedness judgements of backward, forward and symmetric associates in the native and non-native language.

Chapter 5: Relatedness judgements of English word pairs with forward, backward and symmetric association by native and non-native speakers (Study 3)

5.1. Introduction

Study 2 presented in the previous chapter demonstrated that semantic processing is influenced by working memory load. These findings are consistent with the view that semantic processing involves strategic mechanisms that include prospective expectancy generation and retrospective semantic matching (see Section 1.3.3 for detailed discussion). Previous research that aimed to disentangle prospective and retrospective strategies (Thomas et al. 2012; Heyman et al. 2015, 2017; Hutchison et al. 2014) used asymmetric associative priming tasks, in which the materials included forward associates (e.g. *panda – bear*), backward associates (e.g. *ball – catch*) or symmetric associates (e.g. *answer – question*). In these studies, the semantic priming effects in a lexical decision task, i.e. facilitated recognition of words preceded by related as compared to unrelated primes, varied depending on the type of association and was shown to depend on high-level executive functions, such as attentional control (Hutchison et al. 2014) or working memory (Heyman et al. 2015).

All the above studies were conducted in participants' native language (L1). However, the semantic priming phenomenon has also been reported in the non-native language (L2) and in cross-language studies (see Section 1.3.4 for an overview). Semantic facilitation effects in a non-native language have been consistently observed both in the lexical decision task (see Altarriba and Basnight-Brown 2009 for an overview) and in the semantic relatedness task (Thierry and Wu 2007; Wu and Thierry 2010; Morford et al. 2011). Although these findings indicate that semantic activation in a non-native and native language relies on similar mechanisms, there has been limited research directly comparing semantic processing with words presented in a native versus non-native language (Frenck-Mestre and Prince 1997; Ankerstein 2014). Furthermore, there is some evidence that using a non-native language may impose additional demands on working memory (Szmalec et al. 2012; Wen 2016, 2019; see Section 2.4). Based on the findings from Study 2 (Chapter 4), it can be assumed that such increased working memory demands may lead to differences in semantic processing between L1 and L2 and influence strategic mechanisms involved in semantic processing, but no studies so far have focused on strategic processes in semantic processing in L2. Moreover, no studies, either mono- or bilingual, have investigated asymmetric relations in a semantic relatedness task, which requires more in-depth processing of meaning of both words in a pair (see Section 1.4).

To fill the above research gaps, the present study investigated whether and how relatedness judgements of words with different types of association differ in the native and non-native language. It comprised two experiments involving a semantic relatedness task with English word pairs representing forward, backward, and symmetric associations and adapted from Thomas et al. (2012). In Experiment 3.1, participants were native speakers of English, whereas in Experiment 3.2 participants were mostly native speakers of Polish and proficient non-native users of English.

5.2. Aims, research questions and hypotheses

The aim of the experiments presented in this chapter was to study for the first time semantic relatedness judgements of words with different types of association in the L1 and L2 in two different groups of participants.

This study addressed three key research questions:

(1) Is there a facilitation effect of related pairs with forward, backward, and symmetric associations relative to unrelated pairs in the semantic relatedness task in the native language?

(2) How do relatedness judgements of related and unrelated word pairs differ in the native and non-native language?

(3) How are relatedness judgements in the native and non-native language affected by the type of word-pair association?

With regard to the first research question, it was hypothesised that the facilitation effects of related pairs in the semantic relatedness task in the native language would be comparable to the priming effects reported in several lexical decision studies with almost the same set of stimuli (Thomas et al. 2012; Hutchison et al. 2014; Heyman et al. 2017). Study 2 (Chapter 4) found that facilitation effects for closely related pairs in a semantic relatedness task were similar to those observed in a lexical decision task for the same set of Polish stimuli (Rataj et al. 2023). Although the semantic relatedness task, unlike the lexical decision task, requires participants to deliberately process and evaluate the meaning of both words in a pair, related words nonetheless appear to facilitate the recognition of target words and relatedness decisions.

The second hypothesis is related to the qualitative and quantitative differences of facilitation effects in native and non-native speakers. As discussed in Section 1.3.4, previous studies that compared semantic processing in L1 and L2 (Frenck-Mestre and Prince 1997; Phillips et al. 2004; Ankerstein 2014) found similar semantic priming effects in the native and non-native language in lexical decision tasks. Furthermore, non-native speakers in Ankerstein (2014) were overall slower in their lexical decisions but had comparable priming effects relative to native speakers. Based on this research, it was expected in this study that non-native speakers would be slower in their responses than native speakers, but related pairs would result in faster and more accurate relatedness judgements in both native and non-native groups.

The third hypothesis concerns the differential effect of the type of association on relatedness judgements in L1 and L2. As discussed in Section 1.5, the facilitation effect in backward associates likely relies on the retrospective post-lexical matching strategy, while the facilitation in forward associates relies on the prospective expectancy generation strategy (Neely and Kahan 2001; Thomas et al. 2012; Hutchison et al. 2014). However, there have been no prior studies that would explore prospective and retrospective mechanisms in semantic processing in L2. If the present study finds differences in the facilitation effects for asymmetric backward or forward associates between the groups, it will suggest that native and non-native speakers may rely on different strategic mechanisms for semantic processing.

The following sections present two experiments conducted in the native (Experiment 3.1, Section 5.3) and non-native (Experiment 3.2, Section 5.4) language. The experiments involved identical English word pairs and followed the same procedure. The description of each experiment is followed by a brief discussion of results. Section 5.5 present two combined analyses of both experiments differing in the approach to data pre-processing. Finally, Section 5.6 includes an overall discussion of the study followed by key conclusions.

5.3. Relatedness judgements in the native language (Experiment 3.1)

5.3.1. Method

5.3.1.1. Participants

73 students of the University of Nottingham took part in the experiment. However, only data from 62 native English speakers born in the UK were selected for analysis (56 female, 4 male, 1 other, 1 preferred not to state, M_{age} = 18.3 years, SD_{age} = 0.5 years, minimum 18 years, maximum 20 years). The participants were recruited through the SONA experiment management system and received course credit in return for their participation. Most of the participants (N = 55, 89%) were enrolled in the BA program. Most of them were bilinguals or multilinguals: 42 participants (68%) reported knowing at least one foreign language, 15 participants (24%) at least two foreign languages, and five participants (8%) three foreign languages.

5.3.1.2. Design

Similar to the experiments in Study 2 of the thesis, the present experiment was designed using PsychoPy (Peirce et al. 2019) and conducted online using the Pavlovia platform (www.pavlovia.org). The experiment consisted of one session with two counterbalanced blocks and involved a 3 x 2 within-subject design with the independent variables: Type of Association (BA vs FA vs SYM) and Relatedness (related vs unrelated). Response times and accuracy rates were the dependent variables. The experiment was approved by the Ethics Committee of the School of Psychology at the University of Nottingham (Ref. S1371 dated 08/11/2021).

5.3.1.3. Materials

The critical word pairs were adapted from the set of stimuli originally developed by Thomas et al. (2012). Their materials included 180 word pairs divided into three subsets depending on the type association: backward (BA), forward (FA), or symmetrical (SYM). Hutchison et al. (2014) further refined the stimuli and created a better matched set consisting of 40 word pairs for each type of association. These stimuli were subsequently reused by Heyman et al. (2017) and used as the basis by Heyman et al. (2015) for preparing Dutch materials. Because the present study also involved native speakers of Polish (Experiment 3.2), potential English-Polish interlingual homographs (e.g. *car, post*) and cognates (e.g. *ocean, problem*) were removed from the final set. However, they were used in the practice session. The final stimulus set included 30 word pairs in each condition. Within each condition, words (primes) were randomly re-paired with a different target to create unrelated pairs. The list of critical stimuli is provided in Appendix B.

The lexical characteristics of the critical word pairs are presented in Table 26. Whereas the stimuli were originally selected based on the measure of forward and backward association strength between words, cosine semantic similarity values were also calculated for the materials used in the present study. Cosine similarity is a measure of similarity between two word vectors in a semantic space and is calculated as the cosine of the angle between the vectors. It ranges from -1 for completely dissimilar vectors to 1 for identical vectors. Although cosine similarity is not a direct measure of the similarity of meanings, it is often used to compare semantic relatedness of words. It has also been shown that semantic vectors strongly correlate with human relatedness ratings and can effectively predict semantic priming effects in lexical decision tasks (Rataj et al. 2023). In the present study, cosine similarity values demonstrate that associatively unrelated words were also semantically unrelated ($F(1, 178) = 361.7$, $MSE = 5.68$, $p < 0.001$) and that symmetric associates show the highest degree of similarity with no significant differences between forward and backward associates ($F(2, 177) = 6.47$, $MSE = 0.29$, $p < 0.01$). Bonferroni-corrected pairwise comparisons obtained using the emmeans package (Lenth 2021) showed a significant difference between symmetric and both forward ($p < 0.01$) and backward ($p = 0.01$) associates, but no difference between forward and backward pairs ($p = 1$). Unlike the associative strength, however, the similarity value is not directional, i.e. the similarity between prime and target is the same as the similarity between target and prime. Therefore, this measure cannot be used to differentiate between forward and backward associations, but it can provide an indication whether word pairs in a given condition (e.g. BA) are equally semantically related as in another condition (e.g. FA) or not.

Table 26. Characteristics of the critical word pairs in Study 3: word frequency, word length, forward and backward associative strength, and similarity value. Values in parentheses indicate standard errors.

Characteristics	Backward	Forward	Symmetric
Target word frequency[1]	4.11 (0.1)	4.54 (0.1)	4.34 (0.14)
Target word length	5.37 (0.29)	5.00 (0.24)	5.4 (0.25)
Prime word frequency[1]	5.27 (0.1)	3.39 (0.11)	4.71 (0.14)
Prime word length	4.2 (0.19)	6.13 (0.3)	5.17 (0.27)
Forward association strength[2]	0.06 (0.02)	0.48 (0.03)	0.33 (0.02)
Backward association strength[2]	0.37 (0.03)	0.04 (0.01)	0.38 (0.03)
Similarity between related primes and targets[3]	0.42 (0.02)	0.44 (0.02)	0.63 (0.03)
Similarity between unrelated words and targets[3]	0.15 (0.01)	0.1 (0.01)	0.17 (0.02)

Note.

[1] Word frequencies are Zipf values obtained from SUBTLEX-UK (van Heuven et al. 2014).

[2] Forward and backward association strength values were obtained from the “Small World of Words” English word association database (De Deyne et al. 2019).

[3] Similarity values were derived from cosine distances (cosine_similarity = 1 - cosine_distance) obtained via the snaut tool (Mandera et al. 2017), which calculates vector-based distances between individual words based on semantic spaces.

For each participant, stimuli were divided into two lists, each including 15 related and 15 unrelated pairs for each association type (BA, FA, SYM). Targets that were preceded by related words in the first list were preceded by unrelated words in the second list and vice versa. Participants were presented with one list per experimental block. Targets in the lists were pseudorandomized using the pseudorandom list generator (van Heuven, 2020) with the restriction that a maximum of three related/unrelated pairs and a maximum of three pairs with the same association type were presented in a row.

5.3.1.4. Procedure

Before the experiment, participants read an information sheet describing the study and accepted an online consent form in Qualtrics. They were then automatically redirected to the Pavlovia platform where the experiment was administered. They first went through a practice session to get familiar with the semantic relatedness task. During practice, participants received feedback about correct, wrong or late responses. If they reached an 80% threshold in the practice session, they proceeded to the experimental session. Each trial started with a fixation cross for 500 ms, followed by a blank screen for 300 ms. Next, the first word of the pair was presented in lowercase for 150 ms, followed by a blank screen for 50 ms. The second word of the pair (target) then appeared in uppercase. Participants' task was to decide whether or not the second word was semantically related to the first word by pressing the "P" key for related or the "Q" key for unrelated. The uppercase word remained on the screen for 3,000 ms or until response. The intertrial interval was 1,000 ms. The trial procedure is presented in Fig. 23. Each experimental block comprised of 90 trials. Participants had a self-paced break between two blocks.

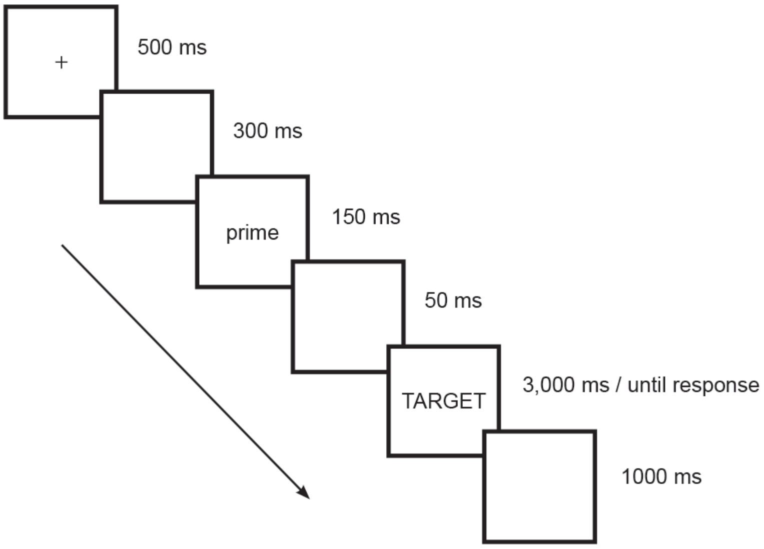

Fig. 23. Experimental procedure of a trial in Study 3.

After the experimental part, participants were redirected back to Qualtrics to complete a demographic and language background questionnaire and a LexTALE task (Lemhöfer and Broersma 2012) to obtain an objective indicator of English proficiency. The total duration of the experiment was around 30 minutes.

5.3.2. Results

5.3.2.1. Data preparation

Four out of 62 native speakers of English who took part in the experiment reported problems with reading (dyslexia, dysgraphia) and their data were removed from the analysis. Another 14 participants who scored less than 85% (averaged % correct) in the LexTALE task were also excluded (for the calculation of the LexTALE score see Lemhöfer and Broersma 2012). Thus, the final sample included 44 participants (37 female, 5 male, 1 other, 1 preferred not to state, M_{age} = 18.3 years, SD_{age} = 0.5 years, minimum 18 years, maximum 20 years). A preliminary analysis of outliers showed that some of the items caused very high error rates, so participants might have either misinterpreted the meaning of these words or their relatedness status was ambiguous. Items for which the error rate was more than 50% were excluded from further analysis. Three such items (targets with both related and unrelated words) were removed (3.3% of the complete dataset): *sentry – annual – GUARD* (FA), *spool – dine – THREAD* (FA), and *fast – short – BRIEF* (BA). Thus, the final data included 28 FA pairs, 29 BA pairs, and 30 SYM pairs.

The analysis of response times was performed after filtering out incorrect responses. Outliers were also removed based on a cut-off value of 2 standard deviations from the mean for each participant and target word. Furthermore, too fast responses (< 250 ms) were removed. In total, 2.55% of reaction time responses were excluded from the analysis.

5.3.2.2. Data analysis

Consistently with Study 2, final data were analysed using generalised linear mixed-effects models (GLMM) in R version 4.1.1 (R Core Team, 2021) with the lme4 package version 1.1.27.1 (Bates et al. 2015).

Fixed effects in the model included Type of Association (BA vs FA vs SYM) and Relatedness (related vs unrelated), and their interactions. The contrasts for Relatedness were calculated using sum coding (-.5 vs .5), whereas the contrasts for the Type of Association were calculated using sum contrasts for three levels of variable with the SYM level as the baseline. The random structure included only random intercepts for subjects and items. After comparing the simplest models using the performance package (Lüdecke et al. 2021), the inverse Gaussian distribution was used for the final analysis because it resulted in better-fitting models (Lo and Andrews 2015). The final model with the default optimizer failed to converge, therefore the BOBYQA optimizer was used.

Final model for the RT analysis: `glmer(rt ~ association * relatedness + (1|subject) + (1|item), data = data.final, family = inverse.gaussian(link="identity"), control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun=1e6)))`.

Final model for the error analysis: `glmer(corr ~ association * relatedness + (1|subject) + (1|item), data = data.final.all, family = binomial, control = glmerControl(optimizer = "bobyqa", optCtrl = list(maxfun = 1e6)))`.

Mean RTs and error rates along with standard errors are summarised in Table 27 and the final model output is presented in Table 28 for the RT analysis and in Table 29 for the error analysis. Mean reaction times for different conditions are illustrated in Fig. 24 and RT differences are presented in Fig. 26 (see Section 5.5, Combined analysis of Experiments 3.1 and 3.2). There was a significant main effect of Relatedness ($p < 0.001$) indicating a facilitation effect regardless of the type of association. Collapsed across the Relatedness factor, reaction times to symmetric associates were significantly different from backward associates ($p < 0.01$), but not from forward associates ($p = 0.4$). The overall significance of fixed effects and their interactions in the model was tested in an analysis of deviance (Type II Wald Chisquare tests) using the car package (Fox and Weisberg 2019). Importantly, it revealed a significant two-way interaction between the Type of Association and Relatedness ($X^2(2) = 33.71$, $p < 0.001$). Bonferroni-corrected pairwise comparisons revealed that the interaction was significant for all types of associations (p's < 0.001): the facilitation effect of related pairs as compared to unrelated pairs was 66 ms for symmetric associates, 35 ms for forward associates, and 31 ms for backward associates.

Table 27. Mean response times and error rates as a function of association type and word-pair relatedness (Experiment 3.1). Values in parentheses indicate standard errors.

Relatedness	Response time (ms)	Error rate (%)
Backward associates (BA)		
Unrelated	702 (13.4)	3.3 (0.51)
Related	671 (13.5)	5.6 (0.66)
Forward associates (FA)		
Unrelated	681 (14.1)	2.2 (0.43)
Related	647 (13.9)	3.7 (0.56)
Symmetric associates (SYM)		
Unrelated	690 (14.0)	2.1 (0.4)
Related	624 (13.9)	1.8 (0.37)

Table 28. GLMM output for the RT analysis (Experiment 3.1).

Factors	*b*-value	SE	*t*-value	*p*-value
Association (BA)	17.281	5.779	2.990	< 0.01
Association (FA)	-4.949	5.930	-0.834	0.4
Relatedness	-43.856	2.735	-16.034	< 0.001
Relatedness x Association (BA)	13.210	4.012	3.292	< 0.001

Relatedness x Association (FA)	8.919	3.873	2.303	< 0.05

Note. BA – backward associates, FA – forward associates.

Table 29. GLMM output for the error analysis (Experiment 3.1).

Factors	*b*-value	SE	*z*-value	*p*-value
Association (BA)	-0.35459	0.21421	-1.655	0.1
Association (FA)	-0.09334	0.21872	-0.427	0.67
Relatedness	-0.32149	0.15093	-2.130	< 0.05
Relatedness x Association (BA)	-0.32006	0.19705	-1.624	0.1
Relatedness x Association (FA)	-0.21449	0.21307	-1.007	0.31

Note. BA – backward associates, FA – forward associates.

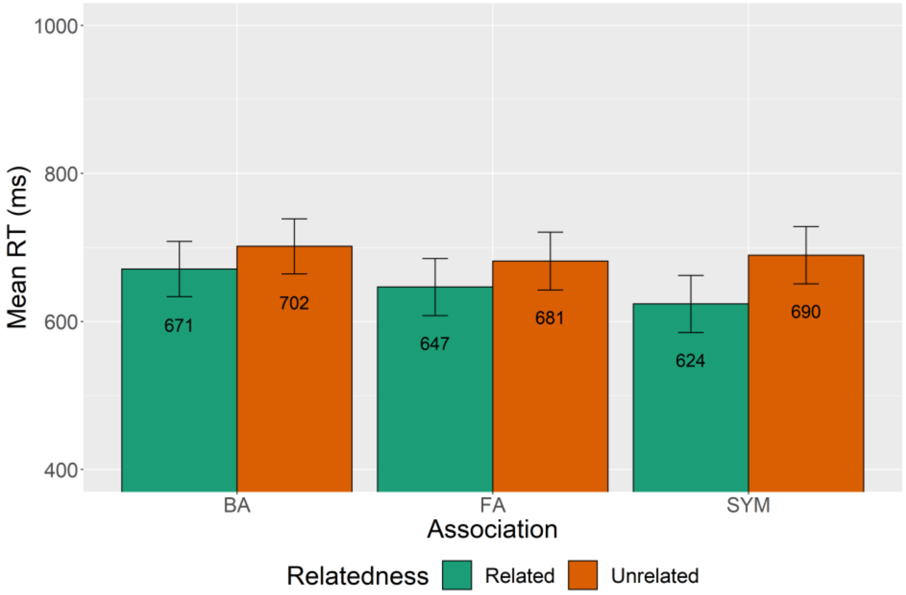

Fig. 24. Mean RTs in the semantic relatedness task as a function of relatedness and type of association in native speakers (Experiment 3.1). Error bars indicate 95% confidence intervals.

The error rate analysis revealed that participants made significantly more errors in response to related as compared to unrelated pairs (3.7% vs 2.5%, $p < 0.05$), but there were no significant differences between the three types of association (p’s > 0.05).

5.3.3. Discussion

The results of the experiment involving native English speakers showed that targets preceded by related words were recognised significantly faster than those preceded by unrelated words regardless of the type of association. Critically, there was an interaction between relatedness and the type of association with symmetric pairs resulting in the highest facilitation effect relative to backward or forward associates. It suggests that both retrospective mechanisms for backward associates and prospective mechanisms for forward associates were engaged in the semantic relatedness judgement task. Thomas et al. (2012) used almost the same stimuli in a lexical decision task with non-degraded and degraded targets. The size of the facilitation effect found in Experiment 3.1 was comparable to Thomas et al.'s results with non-degraded targets (32 ms for BA, 34 ms for FA, and 66 ms for SYM pairs in Experiment 3.1 with a 200 ms SOA; 30 ms for BA, 32 ms for FA, and 52 ms for SYM pairs in Thomas et al.'s (2012) study). The consistency of results indicates that both the lexical decision task and the semantic relatedness task can successfully detect differences in the processing of word pairs with different types of association. However, other experiments that re-used the same materials found slightly different facilitation effect sizes in some of the conditions (cf. 56 ms for BA, 21 ms for FA, and 53 ms for SYM pairs in Hutchison et al.'s (2014) lexical decision task with a 250 ms SOA; 25 ms for BA, 35 ms for FA, and 45 ms for SYM pairs in Heyman et al. (2017) for the low-load condition with a 200 ms SOA), which may be due to variations in the experimental procedure. In these previous studies, the crucial two-way interaction between Relatedness and Type of Association was only reported by Hutchison et al. (2014) although it was due to a smaller priming effect for FA pairs as compared to BA and SYM pairs in contrast to the present experiment in which the interaction was driven by higher facilitation effects for SYM pairs.

Furthermore, the present results show a clear additive pattern for the symmetric pairs with the sum of BA and FA facilitation effects equal to the facilitation effect for SYM pairs (66 ms). Similar results were also reported by Thomas et al. (2012), who suggested that the additive effect indicated that retrospective and prospective processes may independently contribute to the facilitation effects for symmetric pairs.

The error analysis revealed an unexpected reverse effect, i.e. participants made significantly more errors to related than unrelated BA and FA pairs. Presumably, this pattern of responses may stem from the nature of the semantic relatedness task, in which participants have to process the meaning of both words in a pair to judge whether they are related. All previous studies used a lexical decision task, in which it was sufficient to access the lexical representation of the target to decide if it was an existing word.

This experiment investigated relatedness judgements of symmetric and asymmetric associates in the native speakers of English. Experiment 3.2 described in the following section will report on a similar experiment involving proficient non-native speakers of English. The results of both experiments and their implications will be discussed in detail in Section 6.4.

5.4. Relatedness judgements in the non-native language (Experiment 3.2)

5.4.1. Method

5.4.1.1. Participants

38 students of the Faculty of English of Adam Mickiewicz University in Poznan (31 female, M_{age} = 23.4 years, SD_{age} = 5 years, minimum 20 years, maximum 43 years) took part in the experiment. 36 participants were native speakers of Polish, one was a native speaker of Ukrainian, and one was a native speaker of Belarusian and Russian. They were recruited through the university internal recruitment scheme and received course credits in return for their participation. Most of the participants (*N* = 34, 90%) were in the final year of the English BA program, and the others were MA students majoring in English. 33 participants (87%) reported knowing at least one foreign language apart from English.

5.4.1.2. Design, materials and procedure

The design, materials, and procedure were identical to Experiment 3.1.

5.4.2. Results

A similar approach to data pre-processing was followed as in Experiment 3.1. Data from 6 participants who scored less than 75% on the LexTALE tasks were excluded from analysis, which resulted in a final sample of 32 participants. Although the threshold was lower than in the group of native speakers, it corresponded to the advanced level of proficiency users (Lemhöfer and Broersma 2012). Furthermore, senior students at the Faculty of English have passed year-final or entrance exams corresponding to the C1/C2 CEFR level of proficiency. The items which caused high error rates among native speakers were also removed for non-native speakers.

The same procedure for removing outliers was used as in Experiment 3.1, which resulted in the exclusion of a total of 2.36% of RT responses.

Mean RTs and error rates along with standard errors are summarised in Table 30 and the final model output is presented in Table 31 for the RT analysis and in Table 32 for the error analysis. Mean reaction times for different conditions are illustrated in Fig. 25 and facilitation effects are presented in Fig. 26 (see Section 5.5, Combined analysis of Experiments 3.1 and 3.2). There was a significant main effect of Relatedness ($p < 0.001$) revealing an overall facilitation effect of related pairs. Furthermore, the analysis of deviance of the fixed effects in the model revealed a significant overall two-way interaction between Relatedness and Type of Association ($X^2(2) = 15.73$, $p < 0.001$). Bonferroni-corrected pairwise comparisons showed the highest facilitation effect for symmetric associates (79 ms), and the effects for backward associates (44 ms) and forward associates (46 ms) were also significant (p's < 0.001).

Table 30. Mean response times and error rates as a function of association type and word-pair relatedness (Experiment 3.2). Values in parentheses indicate standard errors.

Relatedness	Response time (ms)	Error rate (%)
Backward associates (BA)		
Unrelated	892 (20.3)	3.6 (0.62)
Related	848 (20.3)	7.0 (0.86)
Forward associates (FA)		
Unrelated	894 (21.1)	3.5 (0.62)
Related	849 (21.0)	20.7 (1.38)
Symmetric associates (SYM)		
Unrelated	864 (21.4)	2.8 (0.53)
Related	785 (21.4)	3.4 (0.6)

Table 31. GLMM output for the RT analysis (Experiment 3.2).

Factors	*b*-value	SE	*t*-value	*p*-value
Association (BA)	14.726	8.427	1.747	0.08
Association (FA)	16.162	9.126	1.771	0.08
Relatedness	-56.118	4.271	-13.139	< 0.001
Relatedness x Association (BA)	12.462	5.851	2.130	< 0.05
Relatedness x Association (FA)	10.360	6.138	1.688	0.09

Note. BA – backward associates, FA – forward associates.

Table 32. GLMM output for the error analysis (Experiment 3.2).

Factors	*b*-value	SE	*z*-value	*p*-value
Association (BA)	0.003867	0.258883	0.015	0.99
Association (FA)	-0.676531	0.256281	-2.640	< 0.01
Relatedness	-1.151175	0.144644	-7.959	< 0.001
Relatedness x Association (BA)	0.364194	0.198626	1.834	0.07
Relatedness x Association (FA)	-1.254432	0.192326	-6.522	< 0.001

Note. BA – backward associates, FA – forward associates.

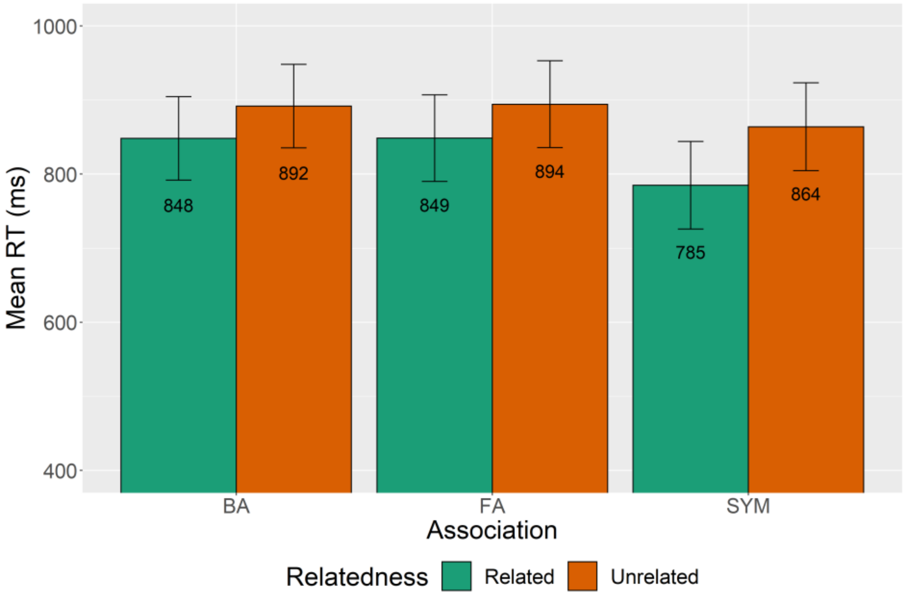

Fig. 25. Mean RTs in the semantic relatedness task as a function of relatedness and type of association in non-native speakers (Experiment 3.2). Error bars indicate 95% confidence intervals.

The error rate analysis indicates that participants made significantly more errors in response to related as compared to unrelated pairs (10.2% vs 3.3%, $p < 0.001$). There was a significant two-way interaction between relatedness and the type of association. Bonferroni-corrected pairwise comparisons revealed that the differences between related and unrelated pairs were significant for BA (7.0% vs 3.6%, $p < 0.001$) and FA (20.7% vs 3.5%) pairs, but not for SYM pairs (3.4% vs 2.8%, $p = 0.36$).

5.4.3. Discussion

The results of the experiment involving non-native speakers of English demonstrate a significant facilitation effect of related pairs for both backward, forward, and symmetric associates. It indicates that similar mechanisms are in place during semantic processing in a non-native relative to native language when L2 proficiency is high. The non-native group also showed an additive facilitation effect for symmetric pairs (79 ms for SYM pairs vs 90 ms for the sum of BA + FA pairs) and there was a two-way interaction between relatedness and the type of association driven by the higher facilitation for SYM pairs.

The overall error analysis revealed that non-native speakers also made significantly more errors when evaluating related than unrelated pairs. However, the FA condition noticeably stands out in this experiment because non-native speakers misjudged on average 20.7% of related pairs with this type of association. It is unlikely that such a low accuracy rate was related to participants' level of proficiency in English because the error rates were much lower for the other conditions, including the unrelated FA pairs that included the same targets re-paired with the same primes in different combinations. Moreover, participants included in the analysis scored high on the LexTALE vocabulary test. A possible explanation of this deviation is that the expectancy-generation mechanisms involved in the processing of forward associates become disrupted or overloaded when participants have to access meaning of words in a non-native language. Alternatively, this surprisingly high error rate for one specific condition may be caused by the characteristics of the stimuli. For instance, some of the words were possibly unfamiliar to non-native speakers (e.g. *sentry* or *shears*) or more frequently used in the British or American variety of English (e.g. *tote* or *dime*).

The following section presents combined analyses of the two experiments conducted in this study and compares relatedness judgements between native and non-native speakers. Section 5.5.1 describes an analysis with all stimuli that were included in by-group analyses of results. However, a high error rate for related FA pairs in the group of non-native speakers (20.7%) raised some doubts concerning the stimuli used for the semantic relatedness task. It also led to unbalanced datasets between two experiments, which might have influenced the between-group analysis. For these reasons, the stimuli that elicited high error rates in the non-native group in the FA condition were removed and the combined analysis was repeated with an equal number of stimuli in each association condition in both groups. This follow-up analysis is described in Section 5.5.2.

5.5. Combined analyses of Experiments 3.1 and 3.2

5.5.1. Combined analysis with all stimuli included in by-group analysis

Mean RTs to related and unrelated word pairs with different types of association are presented in Fig. 24 for native speakers and in Fig. 25 for non-native speakers. RTs from two experiments were compared using a linear mixed-effects model with Language as an additional fixed factor (native vs non-native). The other factors were Type of Association (BA vs FA vs SYM) and Relatedness (related vs unrelated). The random structure included random intercepts for subjects and for items and a by-subject random slope for Relatedness.

The final model used for the combined analysis was: `lmer(rt ~ association * relatedness * language + (1 + relatedness|subject) + (1|item), data = data.final.joined)`.

The complete output of the model is presented in Table 33. Overall, non-native speakers were significantly slower in their responses than native speakers (855 ms vs 669 ms, $b = 139.69$, $SE = 23.54$, $t = 5.94$, $p < 0.001$). The analysis of deviance performed using the Anova function from the car package (Fox and Weisberg 2019) revealed a significant two-way interaction between Language and Type of Association ($X^2(2) = 48.22$, $p < 0.001$). Bonferroni-corrected pairwise comparisons showed that the difference between groups was the largest for forward associates (167 ms, $z = 6.99$, $p < 0.001$) and the smallest for symmetric associates (119 ms, $z = 4.98$, $p < 0.001$), with backward associates falling in-between (133 ms, $z = 5.56$, $p < 0.001$).

Table 33. LMER model output for the combined RT analysis (Experiments 3.1 and 3.2).

Factors	*b*-value	SE	*t*-value	*p*-value
Language	139.688	23.535	5.935	< 0.001
Association (BA)	14.796	5.738	2.579	< 0.05
Association (FA)	8.641	5.798	1.490	0.14
Relatedness	-54.032	5.614	-9.625	< 0.001
Language x Association (BA)	-6.786	4.101	-1.655	0.1
Language x Association (FA)	27.671	4.188	6.607	< 0.001
Language x Relatedness	-20.241	11.222	-1.804	0.08
Relatedness x Association (BA)	11.515	4.107	2.804	< 0.01
Relatedness x Association (FA)	10.302	4.197	2.455	< 0.05
Language x Relatedness x Association (BA)	-2.224	8.201	-0.271	0.79
Language x Relatedness x Association (BA)	1.609	8.376	0.192	0.85

Note. BA – backward associates, FA – forward associates.

A comparison of facilitation effects between two experiments is presented in Fig. 26. The facilitation effect was larger in the non-native than in the native group for all association directions (RT differences between the non-native and native group were 13 ms for BA, 11 ms for FA, and 13 ms for SYM pairs). The model with Language as a factor revealed a trend towards a significant two-way interaction between Language and Relatedness (*p* = 0.08). The breakdown of this interaction using Bonferroni-corrected pairwise comparisons did not reveal significant differences in facilitation effects between native and non-native speakers in either condition (BA pairs: -23 ms, *p* = 0.11; FA pairs: -19 ms, *p* = 0.19; SYM pairs: -20 ms, *p* = 0.15). The three-way interaction between Language, Relatedness and Type of Association was not significant (*p* = 0.96). The models that included the RT difference between related and unrelated pairs instead of reaction times as the dependent variable were not adequate because of many missing datapoints due to errors, especially in the forward association condition in the non-native group.

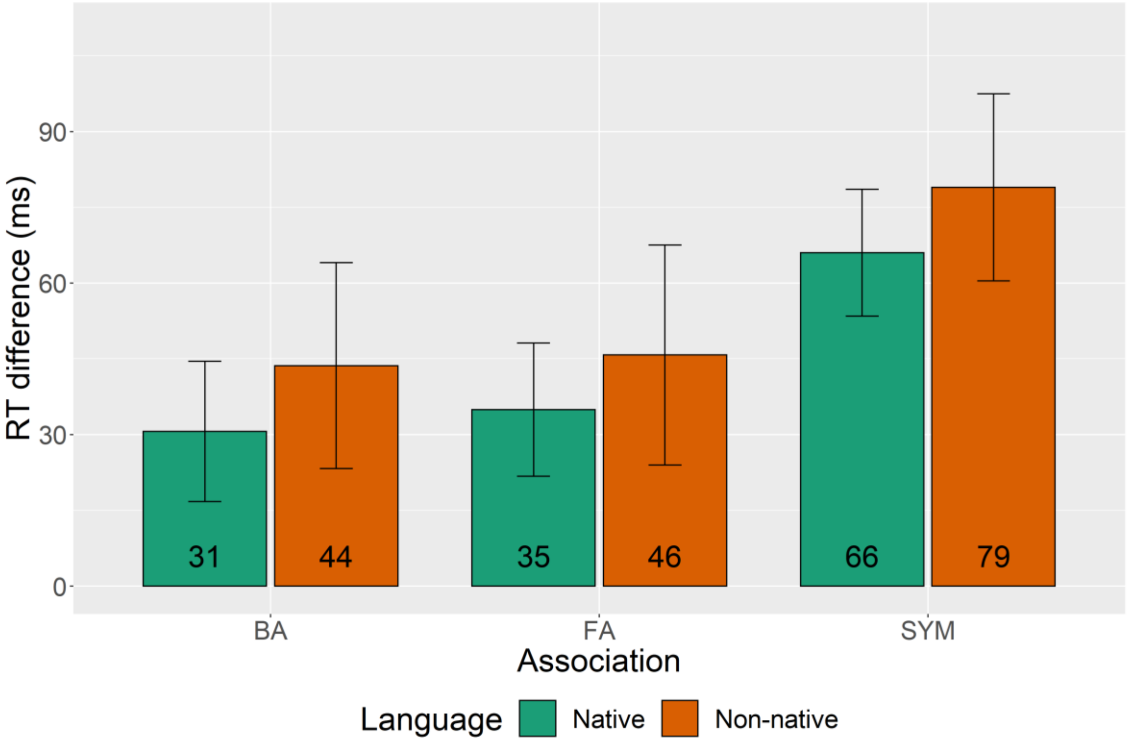

Fig. 26. RT differences between related and unrelated pairs as a function of the type of association in the native and non-native language. Error bars indicate 95% confidence intervals.

The temporal trends of participants' responses were explored using the distributional analysis, similarly to Study 2 (Section 4.2.3.2; see also De Jong et al. 1994; Schwarz and Miller 2012; Perea et al. 2018). Mean response times were summarised across five quantiles (.1, .3, …, .9) for each association direction in each language group. Fig. 27 shows delta plots illustrating RT distributions across quantiles depending on the type of association in the native and non-native language groups.

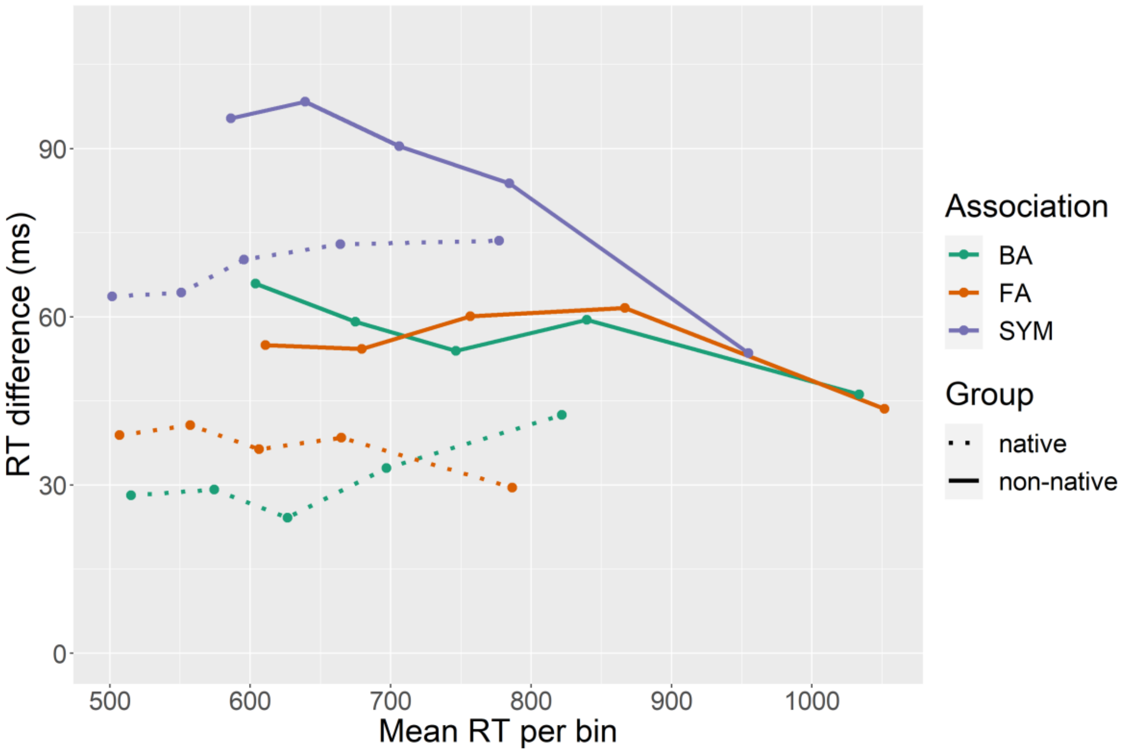

Fig. 27. Differences between reaction times to unrelated and related words as a function of quantile (.1, .3, …, .9) and the type of association in the native and non-native language.

The delta plots allow certain observations and reveal tendencies that cannot be inferred from mean reaction times. First, even the fastest responses in the non-native group came around 100 ms later than those in the native group, meaning that non-native speakers took considerably longer to make a decision about word-pair relatedness regardless of the direction of association. Second, the facilitation effects in the non-native group were larger throughout the entire RT distribution for forward and backward associates. The facilitation effect for symmetric associates was also larger in non-native speakers for faster responses, but sharply reduced in the later quantiles. Third, the facilitation effect was stable throughout the RT distribution for all conditions except for the SYM pairs in the non-native group. Trend analysis was performed using the aov function in R to test whether quantile values showed a linear trend (Fiacconi 2023). The results confirmed that only the negative-going slope for symmetric associates in the non-native group demonstrated a significant linear trend ($F(1) = 4.42$, $p < 0.05$), whereas other conditions did not show linear, quadratic, or cubic trends (p’s > 0.05).

The error analysis showed that non-native speakers made more errors as compared to the native group in all conditions. The error rates were 1.4% higher for related and

0.3% higher for unrelated backward associates; 17% higher for related and 1.3% for unrelated forward associates; and 1.6% higher for related and 0.7% higher for unrelated symmetric associates.

5.5.2. Combined analysis without items that elicited a high error rate in the non-native group in the FA condition

The results of Experiment 2 presented in Section 5.4.2 revealed that non-native speakers made surprisingly more errors in one particular condition (related FA pairs). A by-item error analysis revealed that the high error rate was mostly driven by several word pairs that were most often misjudged by participants. Out of 17 pairs that resulted in a higher than 30% error rate, there were 12 related FA pairs (*sentry – GUARD, spool – THREAD, touchdown – FOOTBALL, crescent – MOON, quill – PEN, tote – BAG, mare – HORSE, shears – SCISSORS, elk – DEER, shutter – WINDOW, hornet – BEE, lumber – WOOD*). It is possible that non-native speakers did not know the meaning of some of the words (e.g. *crescent*, *quill*, or *shears*), so they decided to opt for the “unrelated” answer which in these cases was a proxy for the “Don’t know” answer. A follow-up analysis was conducted after removing the problematic items. First, target words to which a wrong response was given in more than 30% of instances were removed. Pairs with both related and unrelated words were excluded. Most of the removed items (12) were forward associates. To level out the number of items in each condition, a respective number of targets in backward and symmetric pairs with the highest error rates were also removed. As a result, the final dataset in both language groups included 18 word pairs in each association condition. The participant sample was identical to the main analysis and included 44 native and 32 non-native speakers of English.

Mean error rates for both groups are presented in Table 34. The error rate was still the highest for related FA pairs in the non-native group, but the difference was not as considerable as in the main analysis.

Table 34. Follow-up analysis: mean error rates as a function of association direction and word-pair relatedness in native and non-native language. Values in parentheses indicate standard errors.

Relatedness	Error rate (%)	
	Native (Experiment 3.1)	Non-native (Experiment 3.2)
Backward associates (BA)		
Unrelated	1.6 (0.45)	1.9 (0.58)
Related	2.4 (0.55)	1.7 (0.55)
Forward associates (FA)		
Unrelated	1.8 (0.49)	2.8 (0.7)
Related	2.4 (0.56)	5.3 (0.96)
Symmetric associates (SYM)		
Unrelated	2.0 (0.5)	3.6 (0.79)
Related	0.3 (0.18)	1.2 (0.79)

Mean reaction times for both groups are presented in Fig. 28. The RT analysis using the same generalised linear mixed-effects models as in the main analysis revealed a significant main effect of Relatedness in both native and non-native group (b = -55.08, SE = 3.39, t = -16.24, p < 0.001 and b = -66.36, SE = 5.33, t = -12.46, p < 0.001, respectively). Two-way interaction between Relatedness and Type of Association was significant for backward associates in both groups (b = 26.64, SE = 4.86, t = 5.48, p < 0.001 for native speakers, and b = 27.81, SE = 7.4, t = 3.76, p < 0.001 for non-native speakers). Bonferroni-corrected pairwise comparisons of means revealed that the facilitation effects were significant for all association conditions in both groups (p's < 0.001).

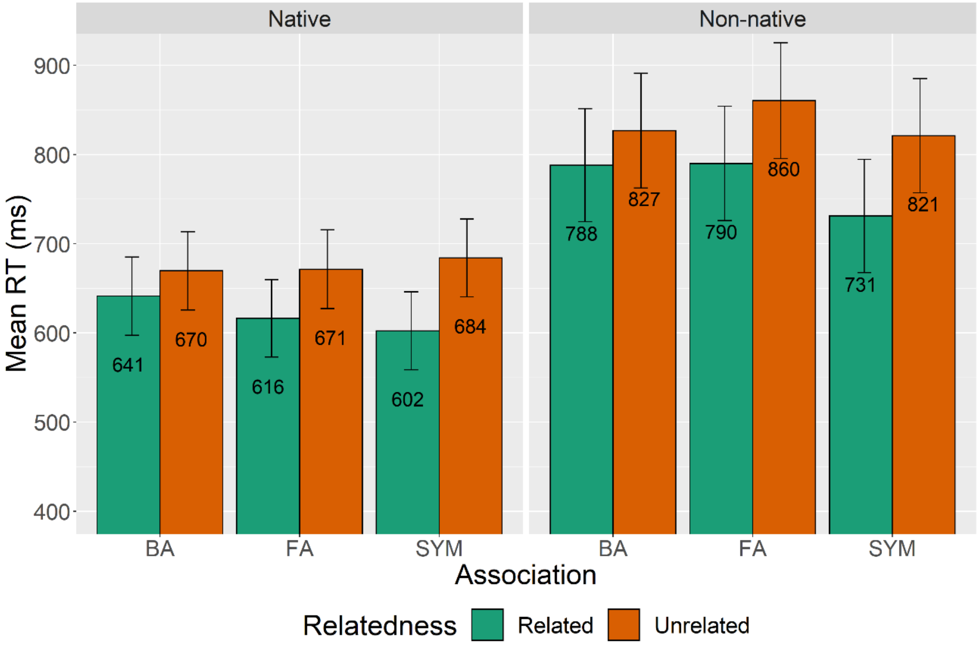

Fig. 28. Follow-up analysis: RT differences between related and unrelated pairs as a function of the type of association in the native and non-native language. Error bars indicate 95% confidence intervals.

A comparison of facilitation effects in the follow-up analysis is illustrated in Fig. 29. The differences in facilitation effects between groups were comparable to the main analysis (non-native speakers were 11 ms faster for BA, 15 ms faster for FA and 8 ms faster for SYM pairs). There was however a noticeable change in the size of the facilitation effect for forward and symmetric associates. Whereas for FA pairs it was 35 ms for native speakers and 46 ms for non-native speakers in the main analysis, the effect soared to 55 ms and 70 ms, respectively, after removing problematic items from the analysis. For SYM pairs, the facilitation effect increased from 66 ms for native and 79 ms for non-native speakers to 82 ms and 90 ms, respectively. At the same time, the pattern of results for the BA pairs remained very similar to the main analysis (31 ms and 44 ms vs 28 ms and 39 ms for the native and non-native group, respectively). Similar to the main analysis, the linear mixed-effects model with Language as a factor found a similar main effect of language ($b = 131.59$, $SE = 23.29$, $t = 5.65$, $p < 0.001$) and an overall two-way interaction between Language and Type of Association ($X^2(2) = 47.34$, $p < 0.001$). Bonferroni-corrected pairwise comparisons showed that the difference in the facilitation effect between groups was significant for all types of associations (BA pairs: 121 ms, $z = 5.08$, $p < 0.001$; FA pairs: 165 ms, $z = 6.92$, $p < 0.001$; SYM pairs: 109 ms, $z = 4.58$, $p < 0.001$). The combined model did not reveal a three-way interaction between Language, Relatedness and Type of Association ($p = 0.98$), but, similar to the analysis with all items, showed a trend towards a significant two-way interaction between Language and Relatedness ($p = 0.09$). Bonferroni-corrected pairwise comparisons did not however reveal significant differences in facilitation effects between native and non-native speakers in either condition (BA pairs: -24 ms, $p = 0.14$; FA pairs: -22 ms, $p = 0.18$; SYM pairs: -21 ms, $p = 0.19$).

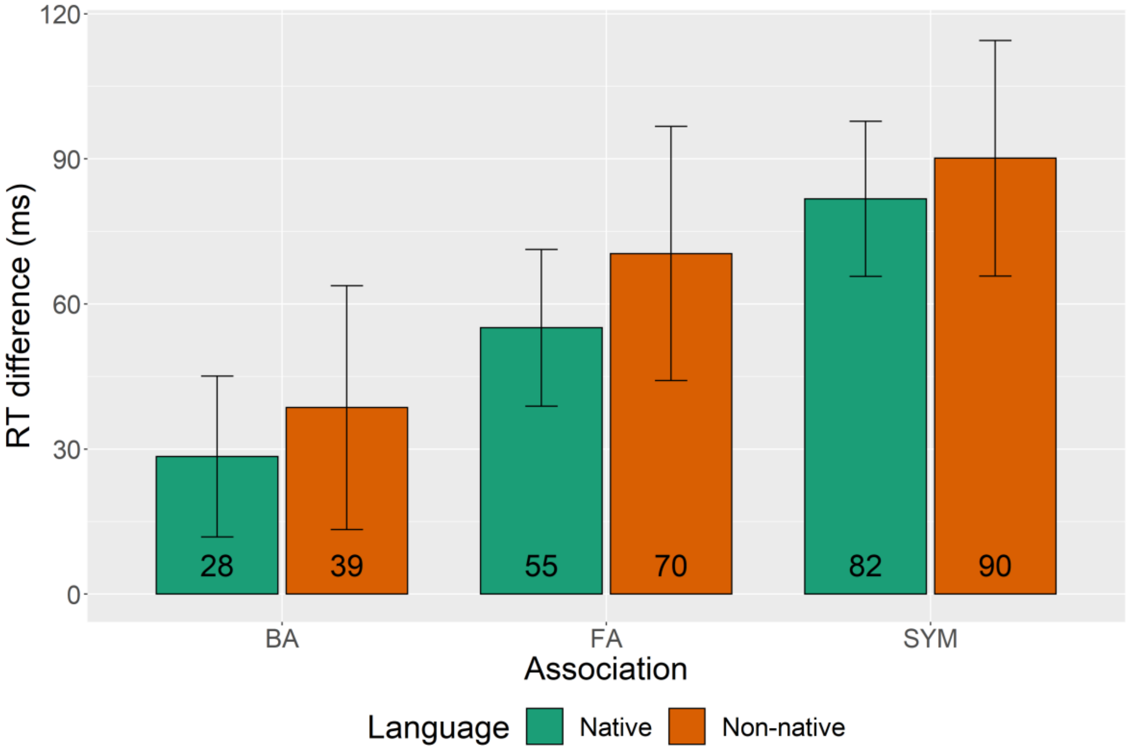

Fig. 29. Follow-up analysis: RT differences between related and unrelated pairs as a function of the type of association in the native and non-native language. Error bars indicate 95% confidence intervals.

The temporal distribution of RT responses is presented in Fig. 30. The facilitation effect was stable across all association types in both groups, with no condition showing statistically significant linear, quadratic, or cubic trends (*p*'s > 0.05). It should be noted that, similarly to the main analysis, the first quantile of responses in the non-native group was around 100 ms slower than that of the native group regardless of the type of association.

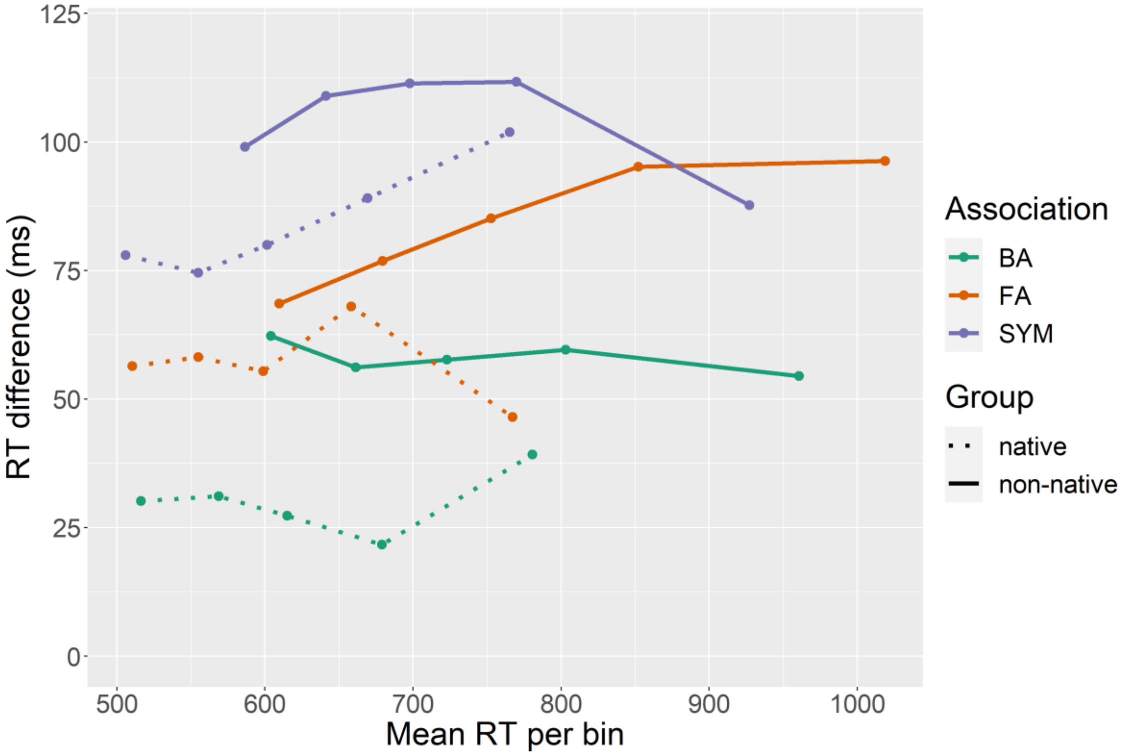

Fig. 30. Follow-up analysis: differences between reaction times to unrelated and related words as a function of quantile (.1, .3, …, .9) and the type of association in the native and non-native language.

5.6. General discussion

The present study focused on semantic relatedness judgements of word pairs with different types of association in L1 and L2. For this purpose, native and advanced non-native speakers of English performed a semantic relatedness task with the same lexical stimuli. The data revealed a significant facilitation effect of related vs unrelated pairs in both groups of participants, suggesting similar semantic activation mechanisms in both native and non-native language. The facilitation effects in the semantic relatedness task in the native group were overall comparable to previous studies that involved lexical decision tasks (Thomas et al. 2012; Hutchison et al. 2014; Heyman et al. 2017), indicating that both tasks can be effectively used to investigate semantic activation and asymmetric associative relations.

Non-native speakers were overall significantly slower at making relatedness judgements as compared to native speakers. Statistical analyses did not reveal significant differences in the facilitation effects between groups although the distributional analysis showed a tendency towards larger facilitation effects in non-native as compared to native speakers, especially for faster responses. This pattern of results may indicate a trade-off between the speed of relatedness judgements and the spreading activation with words presented in the non-native language.

The facilitation effect was observed for all types of association with a summative effect for symmetric associates. Crucially, there was a significant two-way interaction between Relatedness and Type of Association in both groups with symmetric pairs resulting in significantly larger facilitation effects. It should be noted however that symmetrically associated pairs were also characterised by a higher degree of semantic similarity than asymmetric pairs, which may have influenced the results. A difference between the native and non-native group was found for forward associates because non-native speakers made significantly more errors as compared to native speakers or other types of association. Additional analysis with a smaller number of word pairs that caused fewer errors revealed a larger facilitation effect for forward and symmetric associates. This may suggest that prospective strategies involved in the processing of forward associates are particularly modulated by the native/non-native language status and the selection of stimuli. A further detailed discussion of the present findings is provided in Section 6.4.

5.7. Conclusions

In conclusion, Study 3 found that related word pairs resulted in facilitated semantic relatedness judgements as compared to unrelated pairs in both native and proficient non-native speakers of English, but the size of this facilitation effect depended on the type of association. Non-native speakers were however overall slower in their relatedness judgements, which suggests different mechanisms of semantic processing when words are presented in a non-native language as compared to the native language. Furthermore, non-native speakers made more errors than native speakers when judging the relatedness of forward associates, which may suggest that proactive strategies may play an important role in the processing of the non-native language.

Chapter 6: General discussion

6.1. Introduction

The three studies presented in this thesis investigated the impact of semantic and associative relations and working memory on semantic processing in the native and non-native language. The main objective of Study 1 (Chapter 3) was to determine association norms and compare associative and semantic relations for a set of Polish word pairs published by Rataj et al. (2023). It was found that the strength of associative relations showed a positive correlation with the vector-based measure of semantic similarity. Most importantly, however, words that were semantically related to the cue words in Rataj et al. (2023) were rarely provided as free associations by participants in this experiment. Results of Study 1 (Chapter 3) provide evidence that strongly and weakly related word pairs that were used in Study 2 (Chapter 4) represented semantic rather than associative links. Study 2 presented in Chapter 4 investigated whether semantic processing can be influenced by spatial and verbal working memory load. The findings suggest that strongly and weakly semantically related pairs were processed differently, and that semantic relatedness judgements were modulated by working memory load particularly in the verbal domain. The role of the type of word-pair association and the differences between semantic processing in the native and non-native language were further explored in Chapter 5 (Study 3). The results demonstrated that native and highly proficient non-native speakers showed similar patterns of semantic processing and that relatedness judgements depended on the type of associative relations between words because the facilitation effect of related versus unrelated pairs was the largest for symmetrically associated pairs as compared to pairs with only forward or backward association. The current chapter summarises the results of each of the studies presented in this thesis and provides a detailed discussion in the context of previous research in the field. Furthermore, this chapter presents implications for theories and models of semantic memory, outlines the main limitations of the conducted experiments and offers some suggestions for further research.

6.2. Study 1 (Chapter 3) – Polish word associations

6.2.1. Summary

The primary research question of Study 1 concerned the potential overlap of semantic and associative relations in a set of Polish stimuli developed by Rataj et al. (2023) and used in Study 2 of this project (Chapter 4). The original stimuli included targets with two primes that were either semantically strongly (e.g. *hip – KNEE*) or weakly (e.g. *muscle – KNEE*) related to the target. In Rataj et al., semantic relatedness values were obtained from Polish word embeddings (Mykowiecka et al. 2017) and these were compared in two rating surveys. The stimuli were further used in a semantic priming lexical decision task. However, whether the primes and targets were also associated was not investigated. Because there is lack of association data in Polish, Study 1 aimed to establish associative norms for the tested dataset in an online free word associations experiment. The experiment involved 484 participants who provided three associations to each cue word taken from Rataj et al.'s (2023) Polish dataset. A large number of participants and the collection of three responses per cue word made it possible to capture weaker associations as well as investigate potential response chaining.

Study 1 found that only a small percentage of associations (2.6% for all responses combined) overlapped with semantically related targets, suggesting that most of prime-target pairs in the original stimulus set were related semantically rather than associatively. The three cue-response pairs with the highest match rates between associations and semantically related targets included *oprawki* (glasses frame) – *okulary* (glasses), *odrzutowiec* (jet) – *samolot* (plane), and *niedopałek* (cigarette end) – *papieros* (cigarette). These pairs corresponded to semantically strongly related prime-target pairs in the original stimuli. As can be seen, cues and responses in these and most other association pairs (see Table 7 in Section 3.4.4 and Appendix A) were also semantically related, for example, by way of synonymy or meronymy. Indeed, as McNamara put it, "I challenge anyone to find two highly associated words that are not semantically related in some plausible way" (2005: 86). It is also worth noting that the majority of cue words which elicited responses that matched the targets were semantically strongly related primes in Rataj et al. (2023). There were only six semantically weakly related primes, for which either one or two associative responses matched the target. This shows that the prime-target pairs were mainly related semantically rather than associatively.

The second research question of Study 1 addressed the relationship between human-obtained association norms and vector-based semantic similarity measures. The study investigated for the first time the correlation between the measures of associative and semantic relatedness for Polish word pairs. Semantic similarity values obtained from semantic spaces (Mykowiecka et al. 2017; Rataj et al. 2023) were used as an index of semantic relatedness (see details in Section 3.4.5 and means in Table 4, Section 3.4.3). Two measures were used as an index of associative relatedness. The type-to-token ratio (TTR) indicated how many unique responses (types) were given in relation to the total number of responses (tokens). In turn, the associative strength was calculated as the probability of a particular response being given to a cue. Both these indices (see Table 4 in Section 3.4.3) describe the variability of responses, but the TTR characterises the cues, whereas the association strength characterises the responses. For example, if *cat* was given 10 times, *pet* was given five times, and *friend* was given five times as an association to *dog*, the TTR for the cue *dog* would equal 0.15 (three unique responses divided by a total of 20 responses), and the association strength for *cat* would equal 0.5 (10 responses divided by a total of 20).

The results of Study 1 (see Table 8 and Fig. 12 in Section 3.4.5) showed that association strength positively correlated with semantic similarity when responses were grouped both by subject and by cue word. It suggests that responses that more frequently appeared among first associations were also more semantically similar to the cue. This correlation decreased for second and third associations, which may be partly due to the floor effect of the association strength – there were fewer coinciding responses among second and third associations, so most association strength values were low (*M* = 0.09 for second responses and *M* = 0.07 for third responses as compared to *M* = 0.21 for first responses).

The interaction between associative and semantic relations was further illustrated by the negative correlation between TTRs and semantic similarity values. Lower TTR values indicate higher consistency of responses because they mean that there were fewer different types (unique words) among responses. Thus, the negative correlation suggests that associations that were more consistently provided to individual cues (i.e. TTR was lower) were also more semantically similar to these cues. The correlation was less negative for second and third responses, which may also be explained by a high variability of these associations.

The convergent validity of association strength and TTR as measures of associative relatedness was confirmed by a strong negative correlation between them: the fewer unique associations were provided to a cue, the higher was the mean probability of these associations. It is interesting however to look at some individual cue-response pairs that fell out of the general pattern. For example, although mean association strength for second responses was 0.09 (median 0.08), there was one cue with an association strength 0.67. The cue word was *wymiona* (udder), and most participants explicably associated it with *krowa* (cow) first (23 out of 27 responses), and *mleko* (milk) second (18 out of 27 responses). These are marginal examples that, however, were not considered to be outliers because the responses were valid associations.

Vector-based semantic similarity values were also used to detect unconventional response patterns and potential response chaining when participants might have provided associations to their previous responses rather than to the cue word. If the second response was semantically more similar to the first response than to the cue, it might indicate that participants relied on their previous associations for subsequent responses. Overall, little evidence of response chaining was found because second responses were significantly more similar to cues than to first responses, and third responses were significantly more similar to cues than to second responses (see Table 4 in Section 3.4.3). However, the occurrence of response chaining cannot be completely ruled out because there were some participants (13.6%, see Table 9 in Section 3.4.6) whose second associations were on average more similar to their first associations than to cues. The likelihood of response chaining for third responses was very small with only 1.5% of participants providing third responses that were more similar to second responses than to cues.

6.2.2. Discussion and theoretical implications

Before addressing the research questions explored in Study 1, it is useful to briefly discuss the experimental design and methodology. Currently, there are no comprehensive association datasets for the Polish language that could be used as a reliable source of measures of associative relatedness for a relatively large set of words selected for this study. However, large-scale online projects that collect free associations have been conducted in other languages (De Deyne et al. 2013, 2019; Cabana et al. 2023), and they served as a point of reference for the present study. The online format proved to be effective because the experiment was accessible for a wide population and involved participants with different educational background. The brevity and simplicity of the procedure contributed to a low number of outliers in terms of both subjects (4.6%) and responses (2.1%). It should also be noted that, in contrast to some previous Polish (Gatkowska 2016) and English (Kiss et al. 1973; Nelson et al. 1998, 2004) free association studies that focused only on first associations, three responses to each cue word were collected in this study to enable the detection of stronger and weaker associative links (De Deyne et al. 2013).

As described in Section 1.3.2, the differentiation between associative and semantic relations is a widely discussed topic in the literature. Some previous studies have emphasised the importance of distinguishing between associative and semantic relations between targets and primes for studying automatic language processing (Lucas 2000; Perea and Rosa 2002; Hutchison 2003). Whereas it is difficult to single out words that are linked through purely associative or purely semantic relations (McNamara 2005; Kumar 2021), there is evidence that these two types of relations may depend on different mechanisms and be processed differently (Lucas 2000; Perea and Rosa 2002; Hutchison 2003; Ferrand and New 2004; Plaut and Booth 2000; McRae et al. 2012; Ortu et al. 2013; Vivas et al. 2019). The distinction between associative and semantic relations that follows from Study 1 results is consistent with Collins and Loftus' (1975) spreading activation theory of semantic processing. They proposed two sources of activation spreading between nodes in semantic memory. On the one hand, semantic representations may be co-activated if two words are similar in meaning. This type of activation would explain the facilitation effects of semantically related versus unrelated word pairs in a lexical decision or a semantic relatedness task. On the other hand, activation may spread through the lexical network between words that are similar in form or frequently co-occur in language. This would account for similar responses in a free association study or for the facilitation effects of related versus unrelated pairs in studies with associatively related word pairs (e.g. Thomas et al. 2012; Ortu et al. 2013; Hutchison et al. 2014; Heyman et al. 2015; 2017). Furthermore, some distributed models of semantic priming (Masson 1995; Moss et al. 1994; Plaut and Booth 2000) can also account for the effects of lexical co-occurrences. For instance, the single-mechanism account of semantic priming in the lexical decision tasks proposed by Plaut and Booth (2000) can explain both semantic and associative priming by accounting for lexical co-occurrences in the model training parameters. The differentiation between associative and semantic relations is also in line with Ferrand and New (2004), who proposed that associative and semantic priming may rely on word-level and semantic-level loci, respectively. A more recent approach towards the dichotomy of associative and semantic relations (Kumar 2021) suggests treating relatedness as a continuum. Following this line of argument, the present findings indicate that associatively and semantically related words fall within different, although sometimes overlapping ranges of this continuum. Whereas semantically related words may represent more distant links, associations may represent more direct links based on linguistic experience.

Overall, Study 1 drew on two different theoretical approaches to the study of semantic memory. On the one hand, following network-based models, associations collected in the experiment can be represented as interconnected nodes in a network-like structure (Steyvers and Tenenbaum 2005; De Deyne et al. 2016). The relations between associations may vary in strength and may stem from different sources, such as general world knowledge, personal experience, or lexical co-occurrences. On the other hand, semantic similarity values used in Study 1 were obtained using prediction-based distributional semantic models of semantic memory that rely on large text corpora and represent word meanings as semantic vectors (Mikolov et al. 2013; Günther et al. 2019; Kumar 2021; Rataj et al. 2023). There is some theoretical and empirical evidence pointing to a correlation between associative and semantic relations (McRae et al. 2012; De Deyne et al. 2019; Vivas et al. 2019). For example, De Deyne et al. (2019) compared three different measures of semantic similarity (associative strength, pointwise mutual information, and a random walk measure) and demonstrated that association-derived indexes are good predictors of similarity judgements, but their analyses did not consider semantic spaces. Study 1 found a correlation between semantic relatedness measures derived from corpus-based semantic spaces and associative relatedness measures obtained from human data. Following Mandera et al. (2017) and Rataj et al. (2023), these findings indicate that psycholinguistic research can benefit from prediction-based computational language models and suggest that both network-based and corpus-based approaches reliably reflect the structure of semantic memory and can be used complementarily.

6.2.3. Limitations and future research

The word cues in the association study included only words that served as primes in Rataj et al.'s (2023) study because these materials were used in Rataj et al.'s primed lexical decision experiment and in the semantic relatedness task in Study 2 of this thesis. It was therefore possible to check whether semantically related targets were among associatively related responses, but it was not possible to check backward associations, that is whether participants would name primes as associations to targets. The similarity measures based on semantic vectors do not provide this information either because they are non-directional, i.e. the similarity between a prime and a target is the same as between a target and a prime. There are however findings suggesting that the association direction may play a role in strategic language processing and contribute to different semantic priming mechanisms (Hutchison 2002; Hutchison et al. 2014; Thomas et al. 2012; Neely 2012; Heyman et al. 2015, 2017). Therefore, it would be useful to collect both forward and backward associations to be more informed about the bidirectional relations between stimuli. To this end, a follow-up association study with targets used as cue words is currently being conducted.

Another potential limitation, which is not unique to this study, is that the stimulus set used in the experiment was tailored for the needs of this project, and the results of this study may not be generalisable to wider language materials despite a relatively large number of participants. To develop more comprehensive association norms and draw more universal conclusions about associations in Polish, a larger dataset could be collected in a future study. One way how the present study could be scaled up would be by using the so-called snowball technique, which means including the most frequent associations in subsequent iterations of the study. This approach was used, for example, by Gatkowska (2015, 2016) and in the Small World of Words project (De Deyne et al. 2013, 2018; Cabana et al. 2023). A richer dataset with more information about distant associations and cross-links between responses would also open possibilities for more comprehensive statistical analysis and a more refined understanding of associative relationships between words. For example, De Deyne et al. (2019) used a Bayesian approach to evaluate response chaining based on the probability of participants providing an association in response to their previous association rather than the cue. However, this analysis requires a larger dataset with more associations between cues and responses.

A final limitation of the study is related to the availability of semantic spaces and other reference materials for the Polish language. Whereas large databases with various kinds of linguistic and semantic vector information are available in English (Balota et al. 2007; Hutchison et al. 2013; Mandera et al. 2017; Mikolov et al. 2017; De Deyne et al. 2019), the resources are much more limited for Polish. A considerable number of distributional models have been trained by Mykowiecka et al. (2017) using the National Corpus of Polish (Przepiórkowski et al. 2012) and 2016 Polish Wikipedia, but this study and further research would have benefited from more up-to-date models that would take into account the latest advancements in distributional semantics (Günther et al. 2019; Kumar 2021).

6.2.4. Conclusions

In conclusion, Study 1 established associative norms for a set of Polish words that were matched on semantic relatedness (Rataj et al. 2023). Because association data were not previously available for Polish, it was not clear if semantically related words were also associated. Therefore, the key research question of Study 1 was whether semantically related words from a semantic priming dataset were also related associatively. Importantly, the results demonstrated that semantically related word pairs from the tested dataset are minimally associated. This provides crucial evidence that the stimuli from Rataj et al. (2023) can be used to investigate the influence of various factors specifically on the processing of semantic relations. It is particularly relevant for this thesis because

Study 2 presented in Chapter 4 and discussed in the following section used the same stimuli to investigate the influence of different types of working memory load on semantic relatedness judgements. Furthermore, the results of Study 1 showed that association strength positively correlated with similarity values obtained from semantic spaces (Mykowiecka et al. 2017; Rataj et al. 2023). This correlation decreased for second and third responses to the same cue word, but little evidence of response chaining was found.

6.3. Study 2 (Chapter 4) – The impact of spatial and verbal working memory load on relatedness judgements

6.3.1. Summary

Working memory is one of the core executive functions that has important implications for language processing (see Chapter 2). However, there has been limited research on how semantic processing can be affected by spatial or verbal working memory load in the semantic relatedness task (see Section 1.3.3). The aim of Study 2 was therefore to investigate the effect of spatial and verbal working memory load (high vs low) on semantic relatedness judgements of word pairs with different relatedness strength. In Experiment 2.1, a dual-task approach was employed, in which each experimental trial involved relatedness judgements combined with an additional task that taxed working memory in the spatial or verbal domain. In addition to semantically strongly related and unrelated pairs, stimuli in the relatedness judgement task also included weakly related pairs, which were expected to be more affected by the secondary working memory task than strongly related pairs due to weaker semantic links between the words. Furthermore, two control experiments were conducted. Experiment 2.2 followed the procedure of Experiment 2.1 but did not include the working memory task to establish the pattern of relatedness judgements without additional working memory demands. To check whether this pattern depended on the task procedure (Ortu et al. 2013), in Experiment 2.3 participants made a relatedness decision when they saw a response cue 1050 ms after the presentation of the target word. There are mixed findings in the literature with regard to the processing of the intermediate relatedness condition (Kuperberg et al. 2008; Ortu et al. 2013; Rataj et al. 2023), so control experiments particularly focused on the inhibition effect for semantically weakly related pairs initially observed in Experiment 2.1.

The first research question of Experiment 2.1 concerned the impact of working memory load on semantic relatedness judgements. Following Heyman et al. (2015, 2017), an overall effect of load on relatedness judgements was expected, i.e. participants were predicted to be slower and less accurate in their responses when their working memory was taxed more. The results confirmed this hypothesis revealing the main effect of load in both the working memory and the semantic relatedness task in both RT and error analysis.

The second research question of Experiment 2.1 investigated the influence of working memory task on semantic relatedness judgements. The verbal working memory task was expected to have a larger impact on relatedness judgements than the spatial working memory task because it additionally constrained resources in the verbal domain that are relevant for semantic processing. The main effect of task confirmed this hypothesis because taxing working memory in the verbal domain resulted in slower responses in the semantic relatedness task compared to spatial working memory.

The impact of verbal and spatial working memory load (high and low) on semantic relatedness judgements of semantically strongly and weakly related pairs was the focus of the third research question of Experiment 2.1 (cf. Heyman et al. 2015, 2017; Radel et al. 2015). The data revealed that, relative to semantically unrelated word pairs, responses were faster for semantically strongly related pairs but slower for semantically weakly related pairs. Importantly, the results confirmed the hypothesis about the differential effect of the type of the working memory task on relatedness judgements of strongly and weakly related pairs. In the verbal working memory condition, the facilitation effect for strongly related pairs was weaker, whereas the inhibition effect for weakly related pairs was stronger relative to the spatial working memory condition. Another crucial finding is that, whereas the task had a significant effect on both relatedness conditions, the crucial three-way interaction between load, task and relatedness was only significant for weakly related pairs. The more difficult 2-back working memory task increased the inhibition effect in the verbal but not in the spatial condition (see Table 17 and Fig. 16 in Section 4.2.3.2). This confirmed the assumption that weakly related pairs would be more sensitive to the working memory manipulation, in line with Radel et al.'s (2015) findings of increased facilitation effect for indirectly related pairs under high inhibition demands.

Because semantic processing in the semantic relatedness task can be affected by task demands (cf. Kuperberg et al. 2008; Ortu et al. 2013), the research question about the differences between relatedness judgements of semantically strongly and weakly semantic pairs was further addressed in Experiments 2.2 and 2.3. As predicted, participants in all experiments were significantly faster in their responses to strongly related than to unrelated word pairs. Unexpectedly, however, responses to weakly related pairs were overall slower than to unrelated pairs regardless of the additional working memory load, which was contrary to some previous findings of a weaker facilitation effect for weakly or indirectly related pairs as compared to strongly or directly related pairs (Ortu et al. 2013; Radel et al. 2015; Rataj et al. 2023). This inhibition effect initially observed in Experiment 2.1, which involved a concurrent working memory task, was also found in Experiment 2.2 without the working memory manipulation. Following Ortu et al. (2013), Experiment 2.3, which also did not involve working memory manipulation, aimed to verify whether adding a response cue that introduced a delay between target presentation and the relatedness judgement impacted RT differences for weakly and strongly related word pairs. The findings revealed that the size of the inhibition effect for weakly related pairs was not affected by this change in the procedure. The facilitation effect for strongly related pairs decreased although it was still significant when relatedness judgements were delayed.

Overall, the results of Study 2 show that working memory type and load influence semantic relatedness judgements, but the direction and size of the impact depend on the strength of semantic relations.

6.3.2. Discussion and theoretical implications

Three experiments conducted within Study 2 relied on the well-established finding of facilitated processing of related relative to unrelated word pairs (Meyer and Schvaneveldt 1971; Neely 1976; McNamara 2005) and followed the localist (Collins and Loftus 1975) and distributed (Masson 1995; Moss et al. 1994; Plaut 1995; Plaut and Booth 2000) spreading activation accounts of semantic processing positing that semantic activation from the presented word is spread to related concepts in the semantic memory network and can therefore facilitate their recognition. Whereas the activation spreading may stem from both associative and semantic links between words (see Section 1.3.2 and discussion in Section 6.2.2), Study 2 focused specifically on semantic relations. As was found in Study 1 presented in Chapter 3 and discussed in Section 6.2, the word pairs used in Study 2 were predominantly related semantically rather than associatively. Furthermore, the main focus of Study 2 was on the influence of working memory type and load on semantic processing. Working memory is regarded as a limited-capacity system for storing and handling immediately relevant information (Baddeley and Hitch 1974; Cowan 1999; Barrouillet and Camos 2007, 2020; Cowan 2010; Baddeley 2011; Baddeley et al. 2020). It is closely linked to language comprehension and processing as well as other executive functions, such as attentional and inhibitory control (Shah and Miyake 1996; Miyake et al. 2000; Diamond 2013). Previous psycholinguistic studies found that high-order executive functions, such as working memory (Heyman et al. 2015) and attentional control (Hutchison et al. 2014), may affect semantic processing. Also, as was shown in Chapter 2.5, there is evidence from non-linguistic studies pointing to separate mechanisms for verbal and spatial working memory (Engle et al. 1999; Kane et al. 2004; Conway et al. 2005; Kim et al. 2005; Zhao et al. 2010; Clouter et al. 2015). Study 2 combined these lines of research by investigating the differential impact of spatial and verbal working memory load on semantic relatedness judgements of strongly and weakly related pairs.

The first two research questions of Experiment 2.1 concentrated on whether working memory load (high vs low) and task (verbal vs spatial) would impact semantic relatedness judgements. The working memory load in this study was manipulated using the n-back task (Kane et al. 2007; Clouter et al. 2015): participants were asked to remember stimuli (dots or letters) from the previous trial (1-back, low load) or from two trials before (2-back, high load). Previous semantic priming lexical decision studies that investigated the effect of working memory manipulated the load by varying the stimuli pattern difficulty, e.g. digits and letters in Perea et al. (2018) or dots in Heyman et al. (2015, 2017). The overall effect of load in Experiment 2.1 suggests that participants' resources were taxed significantly more in the 2-back than in the 1-back working memory task. This result indicates that the n-back paradigm was effective in manipulating the difficulty of the working memory task.

The working memory task in Experiment 2.1 was manipulated by presenting verbal or non-verbal stimuli. The spatial task involved remembering dot locations, whereas the verbal task involved remembering letters and thus imposed additional constraints on the resources required for analysing lexical and semantic information. As far as I am aware, no previous studies have investigated the differential effect of verbal and spatial working memory on relatedness judgements. Overall, participants in Experiment 2.1 were slower at making relatedness judgements when verbal working memory was taxed compared to spatial working memory. These results suggest that the spreading of activation between related words is influenced by working memory load in the verbal domain. This may be because activation spreading between words or the activation of the target becomes impeded under working memory load in the shared verbal domain. It is therefore possible that the type of working memory taxed in the concurrent task rather than the difficulty of the task is important for semantic processing. More generally, these findings provide additional evidence supporting the functional separability of verbal and spatial working memory resources (Shah and Miyake 1996; Nagel et al. 2007; Zhao et al. 2010; Clouter et al. 2015; Swanson 2017).

The third research question of Experiment 2.1 addressed the differences in the effects of working memory type and load on semantically strongly and weakly related pairs. This question partially overlaps with the research questions of Experiments 2.2 and 2.3 that involved different procedures and focused on the processing of semantically strongly and weakly related pairs without the working memory manipulation, so the results of all three experiments and their implications will be discussed together below.

As expected, participants in all experiments were significantly faster making decisions about semantically strongly related than unrelated pairs regardless of the delay between target presentation and decision. This facilitation effect was consistent with other studies that used the semantic relatedness task (Balota and Paul 1996; Kuperberg et al. 2008; Ortu et al. 2013). Surprisingly, however, participants were significantly slower in their judgements of semantically weakly related than unrelated pairs. As far as I am aware, there are only two published studies that used word pairs with an intermediate relatedness condition in a semantic relatedness judgements task. A linear priming pattern was reported by Ortu et el. (2013) with the fastest responses to highly associated pairs (e.g. *cherry – tree*), slower responses to moderately associated pairs (e.g. *camera – lens*) and the slowest responses to unrelated pairs (e.g. *mirror – thumb*). In contrast, Kuperberg et al. (2008) found an inhibition effect for indirectly related pairs that were linked through a mediating word (e.g. *lion – (tiger) – stripes*) relative to unrelated pairs. The procedure of Experiments 2.1 and 2.2 was similar to the procedure used in Kuperberg et al. (2008) because participants immediately responded to the second word (target), which was preceded by semantically strongly, weakly or unrelated words. In contrast, Experiment 2.3 introduced a response cue and a 1050 ms delay after the target presentation similar to Ortu et el. (2013). However, the inhibition effect for semantically weakly related pairs was consistent across all three experiments regardless of the procedure or the presence of additional working memory load. The findings provided evidence that the spread of activation and its strength may depend on the degree of relatedness between words in a pair. Thus, semantically weakly related pairs consistently inhibited the recognition of target words, while semantically strongly related pairs facilitated it as compared to unrelated pairs.

It was found that additional working memory load specifically in the verbal domain, which was relevant for the linguistic task, influenced relatedness decisions by weakening the facilitation effect for strongly related pairs and enhancing the inhibition effect for weakly related pairs. Critically, high verbal working memory load increased the inhibitory effect for weakly related pairs but did not impact the facilitatory effect for strongly related pairs. A possible explanation for this finding is that weaker semantic links between weakly related words become incrementally difficult to judge under increased working memory load in the shared verbal domain. This finding can also be explained within the framework of research on the interaction between working memory and language. Thus, according to the multicomponent model (Baddeley and Hitch 1974; Baddeley 2011; Baddeley et al. 2020), the phonological loop, which is responsible for language processing, is separate from the visuo-spatial sketchpad, which is mostly responsible for processing non-verbal information. Semantic processing can also be linked to the semantic buffer (Martin 2021) and executive components (Wen 2019), which are distinguished from non-verbal working memory components. When working memory was taxed specifically in the verbal domain, the load had an impact on the processing of ambiguous semantic links between weakly related words. This was not the case when taxing working memory in the spatial domain, which did not require cognitive resources needed for making semantic relatedness decisions.

Relatedness judgements for weakly related pairs were less straightforward and showed high variability. Participants in all experiments found it difficult to decide whether weakly related pairs were related or not because the error rate ranged from 25%

in Experiment 2.3 to 30% in Experiment 2.1 with the additional working memory load. However, it might be more appropriate to treat the accuracy rate for weakly related pairs in the semantic relatedness task as a measure of consistency rather than as accuracy. Kuperberg et al. (2008) also pointed out the subjectivity of responses to indirectly related pairs and reported an even higher error rate of 50% for indirectly related pairs in the semantic relatedness task. Furthermore, individual strategies may play a more significant role when people are not certain about their responses. Although the instructions before the experiment prompted participants to choose the “related” response when in doubt, some participants may have opted for the “unrelated” response when they were not sure about the relationship between the words even if they were weakly related.

A possible explanation for the differences between relatedness conditions is that the first word that is presented (prime) in weakly related word pairs may pre-activate concepts with stronger semantic links than the actual target. The need to suppress these semantic competitors may contribute to longer responses and higher error rates as opposed to strongly related pairs where the target word has strong semantic links to the prime. When a delay was introduced in Experiment 2.3, the facilitation effect for strongly related pairs decreased because the pre-activation of targets by strongly related words may have attenuated over time. In contrast, the inhibition effect persisted even with delayed judgements because the suppression of irrelevant semantically related words not relevant for the actual relatedness decision may require more time and executive resources. This result would also be in line with Radel et al.’s (2015) finding of a larger priming effect for weakly related pairs when participants’ inhibitory resources were strongly depleted before the semantic priming lexical decision task, which suggests a higher speed of spreading activation and easier activation of weakly related concepts when the suppression mechanisms are disrupted.

When verbal working memory resources were taxed in a high-load task in Experiment 2.1, the weakly related word pairs were particularly affected and resulted in increased inhibition relative to a low-load task. A demanding verbal working memory task appeared to impose additional restraints on the speed of activating weakly related concepts. Presumably, under additional cognitive load, it was more difficult for the participants to access the meaning of the target word and/or make a decision about its relatedness to the first word (prime) in the presence of more strongly related candidates activated by the prime. The differences between the processing of strongly and weakly related pairs are illustrated in Fig. 31.

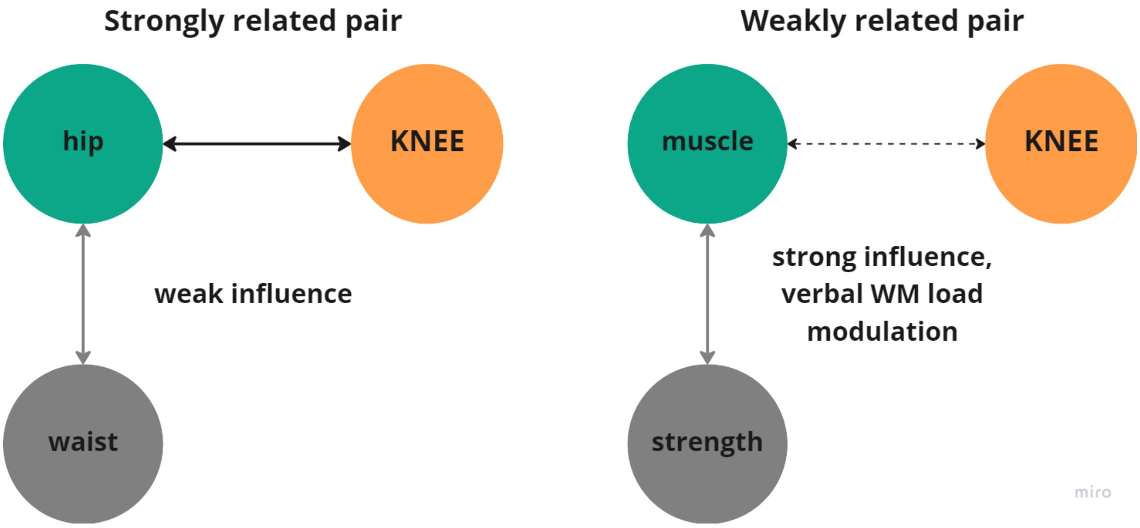

Fig. 31. Interaction between strongly (left panel) and weakly (right panel) related word pairs. Green circles indicate the prime, orange circles indicate the target, and grey circles indicate potential competitors. Solid lines indicate a strong semantic relationship, and dotted lines indicate a weak semantic relationship. Strongly related competitors have a weak influence on the processing of strongly related pairs, but they have a strong influence on the processing of weakly related pairs, which can be modulated by high verbal working memory load.

In a strongly related pair, the first word (prime) *hip* presumably pre-activates several strongly related concepts, among which is the target *KNEE* and a number of others, for example, *waist*. When the strongly related target word is presented, other pre-activated concepts may have a weak influence on the relatedness decision, so the response is quick and a facilitation effect is observed. In contrast, for a weakly related pair, the first word (prime) *muscle* may also pre-activate strongly related concepts, for example, *strength*, but the target *KNEE* is not among them due to weaker semantic links. When the target word is presented, other more strongly related concepts will have a strong influence on the relatedness judgement and their pre-activation needs to be suppressed before making a decision about the weakly related target. The competition of other candidates with stronger semantic links than the actual target therefore will result in the inhibition effect and less consistent responses for weakly related pairs. These pairs are also particularly modulated by the additional high verbal working memory load, as was found in Experiment 2.1.

The delta plots for Experiment 2.1 (see Fig. 17 in Section 4.2.3.2) provided additional support to this assumption. The distributional analysis revealed insights into the dynamics of the effect of the working memory task and load and indicated that the pattern of results is stable across the entire response time distribution. The verbal working memory task consistently reduced the facilitation effect for strongly related pairs and increased the inhibition effect for weakly related pairs. High working memory load resulted in a larger difference between the verbal and spatial task only for weakly related pairs, but not for strongly related ones. An advantage of the delta plots is that they demonstrate the time course of the relatedness effects, which cannot be inferred from linear models or descriptive statistics. First, Fig. 17 shows an increasing trend for both the facilitation and the inhibition effect in all conditions, except for the low-load verbal working memory load where the effect is rather stable across the RT distribution. The increasing facilitation effect for slower responses corresponds to the common finding in the literature suggesting that many experimental manipulations, including those in semantic priming studies, usually affect slower responses more than faster ones (Pratte et al. 2010; Roelofs et al. 2011; Schwarz and Miller 2012; Ellinghaus and Miller 2018). However, the delta plots for weakly related pairs represent an opposite tendency with the effect of relatedness diminishing over time and causing slower responses as compared to unrelated pairs. A similar downward pattern has been reported, among others, for the Simon task (Schwarz and Miller 2012) and the masked semantic priming task (Ellinghaus and Miller 2018) and has been termed a decreasing, or a negative-going delta plot (nDP). One of the proposed explanations for nDPs stems from the activation-suppression hypothesis suggesting gradual inhibition of responses due to the suppression of irrelevant information in a conflict task (De Jong et al. 1994; Burle et al. 2002; Ridderinkhof et al. 2004). For weakly related pairs in a semantic relatedness task, the irrelevant information that needs to be suppressed may involve semantic links to more strongly related concepts than the actual target word. Further increase in the inhibition effect under high verbal working memory load in Experiment 2.1, especially for RTs between 800 ms and 900 ms, may indicate that the suppression of competing semantic information requires executive control that can be affected by high working memory load in the shared domain.

The type of task used in Study 2 may also have contributed to the effects of concurrent spatial and verbal working memory load on semantic processing. The nature of the semantic relatedness task, in which participants decide whether pairs of words are semantically related or not (e.g. Balota and Paul 1996; Faust and Lavidor 2003; Kuperberg et al. 2008; Ortu et al. 2013; Gilbert et al. 2018), requires participants to remember the first word and process the meaning of two words to make a decision about the relatedness of the word pair. This decision is different from the one in the lexical decision task, in which participants decide whether or not a target string of letters is an existing word (e.g. Neely 1976; Lucas 2000; Hutchison et al. 2013), thus it is the lexical status of the target item that is evaluated. Previous studies that explored the effects of working memory load on semantic processing (Heyman et al. 2015, 2017) focused on automatic versus strategic processes in semantic priming, for which purpose the lexical decision task is more appropriate because it taps into automatic spreading of semantic activation. These studies also manipulated the SOA (200 ms vs 1200 ms) with a fixed prime presentation duration (150 ms) to investigate automatic versus strategic processing. Because of the differences in research questions and methodology, it is difficult to make direct comparisons between the findings of Study 2 and Heyman et al.'s (2015, 2017) results, but it seems that the working memory demands inherent in relatedness judgements make semantic processing in the semantic relatedness task more sensitive to concurrent working memory load. Therefore, the semantic relatedness task is likely more suitable for studying possible effects of different types of working memory load on semantic processing because participants need to retrieve the meaning of both words in a pair and expressly judge their relatedness (Balota and Paul 1996; Poort and Rodd 2019).

6.3.3. Limitations and future research

Previous research has shown that individual variations in executive abilities may modulate performance on various tasks. For example, Hutchison et al. (2014) found that participants who performed better on attentional control tasks were more likely to engage in prospective expectancy generation processes, whereas participants with lower attentional control scores were more likely to rely on retrospective strategies. It is therefore possible that the differential effects of verbal and spatial working memory load on relatedness judgements reported in this thesis might be dependent on differences in working memory capacity (WMC). The WMC measure was originally developed to demonstrate a correlation between individual working memory and comprehension abilities (Daneman and

Carpenter 1980) and was later extensively used in different versions to demonstrate the dependency between individual WMC and, among others, attentional control (Colflesh and Conway 2007), strategic processing (Kiefer et al. 2005; Ortells et al. 2017, 2018; Fernández et al. 2021), and semantic priming (Kiefer et al. 2005; Ortells et al. 2016). Different versions of WMC tests were developed to measure both visuospatial and verbal memory. Although varying in details, most of WMC measures usually involve a span task that reflects storage capacity and a processing task that reflects executive abilities (Engle and Kane 2003; Kane et al. 2004; Conway et al. 2005; Unsworth et al. 2009). To the best of my knowledge, however, there are no publicly available tests of verbal and spatial WMC in the Polish language, and the development of such a test was outside the scope of this thesis. Therefore, these individual differences in WMC were not examined in this study, which might be a potential caveat. Future research on the influence of working memory on semantic processing would benefit from incorporating WMC measures as an indicator of individual executive abilities.

The choice of the working memory manipulation in the dual-task approach employed in Experiment 2.1 might be seen as another potential limitation. It may be argued that the task in which participants have to match a dot or a letter against a previously presented item engages the storage rather than the executive component required for processing and manipulating information in the working memory. It is suggested in the literature that a task involving the reproduction of items (e.g. Heyman et al. 2015, 2017) or deciding whether an item appeared in a set presented earlier (e.g. Paap and Noel 1991; Perea et al. 2008) would impose a higher load on the executive component of working memory. However, the results of Experiment 2.1 demonstrate that our manipulation was effective because there was a significant effect of load in both the working memory and the semantic relatedness task. Introducing a more challenging secondary task might have tampered with the flow of the dual-task trials and resulted in higher error rates, especially in the high-load condition. In addition, a similar secondary task was successfully used in other studies involving verbal and spatial working memory (e.g. Clouter et al. 2015).

Furthermore, additional research is needed to explore mechanisms involved in relatedness judgements and the influence of executive functions on semantic processing. Study 2 demonstrated that semantic relatedness judgements can be modulated by the type of working memory load and that this modulation may differ in size and direction depending on the strength of semantic relatedness between words in a pair. Semantically weakly related pairs were particularly sensitive to working memory manipulations and showed an unexpected inhibition effect relative to unrelated pairs. However, it is not clear from the reaction time data whether additional working memory load affected the activation of target words, the spread of activation between words, or the decision-making processing involved in explicit relatedness judgements required by the task. Disentangling these processes would be possible, for example, with the use of brain imaging techniques which offer a high temporal resolution, such as electro- and magnetoencephalography. Moreover, there is evidence that, apart from working memory, semantic processing can be affected by other executive functions, such as attentional (Hutchison et al. 2014) and inhibitory control (Radel et al. 2015). Therefore, future studies could use a similar dual-task design with a different secondary task to verify whether the effect of working memory on relatedness judgements found in Experiment 2.1 can be generalised to other high-order cognitive functions.

Finally, all experiments in the study were conducted online, which might involve certain risks regarding the control over confounding factors. Web-based studies are only just beginning to gain popularity as an alternative to lab-based environments; however, the emergence of high-precision tools for building, hosting and administering psycholinguistic experiments makes it possible to conduct end-to-end research outside the lab. Experiments in this study were built in PsychoPy and hosted on the Pavlovia platform because both these tools were developed specifically for behavioural studies involving reaction times and offer a great degree of flexibility. Overall, there are certain implications of online data collection. For example, absolute reaction time measurements were shown to have more variability due to the use of different operating systems and browsers (Bridges et al. 2020). However, our experiments involved a within-subject design, in which between-condition differences are more crucial than absolute values. Naturally, there is less control over the participants' environment and behaviour during the experiment in online studies, which has its pros and cons. On the one hand, there is larger variability in data and a higher risk of dropouts. On the other hand, there is a lower chance of participant bias, and ecological validity is higher because participants complete the experiment in a more naturalistic environment at a convenient time. Being aware of these limitations is important when designing and running online experiments. Some high-level recommendations for improving the quality of online research formulated by Sauter et al.

(2020) were followed in this study, in particular regarding comprehensive instructions for participants, providing intermediate feedback, and thorough piloting and troubleshooting.

6.3.4. Conclusions

The main objective of Study 2 was to investigate how the processing of word pairs with different degrees of semantic relatedness is affected by different types of working memory load. The findings revealed that semantic processing is influenced more strongly by verbal working memory demands, with reduced facilitatory effect for strongly related pairs but increased inhibitory effect for weakly related pairs, compared to a spatial working memory task. Critically, high verbal working memory load increased the inhibitory effect for weakly related pairs but did not impact the facilitatory effect for strongly related pairs. The influence of verbal working memory load on responses to weakly related pairs indicates that the processing of words with a lower degree of semantic relatedness is in particular affected by verbal working memory load. These results are in line with the theoretical models of working memory that distinguish between verbal and visuospatial components (Baddeley and Hitch 1974; Baddeley 2011; Baddeley et al. 2020) and previous empirical findings suggesting a differential effect of verbal and spatial working memory load on other cognitive functions (Shah and Miyake 1996; Nagel et al. 2007; Zhao et al. 2010; Clouter et al. 2015; Swanson 2017). Furthermore, the results of Study 2 lend additional empirical support to the views assuming the dependency between semantic processing and high-order executive functions (Neely 1991; Neely and Kahan 2001; Thomas et al. 2012; Hutchison et al. 2014; Heyman et al. 2015; Radel et al. 2015).

The findings also revealed that, regardless of the presence of additional working memory load or delay between target presentation and relatedness decision, relatedness judgements were faster for semantically strongly related pairs but slower for semantically weakly related pairs relative to unrelated word pairs. This difference in the response patterns was consistently observed throughout the RT distribution. The inhibition effect for semantically weakly related as opposed to the facilitation effect for semantically strongly related pairs was interpreted in the context of the spreading activation model of semantic processing (Collins and Loftus 1975) and the activation-suppression hypothesis (De Jong et al. 1994; Burle et al. 2002; Ridderinkhof et al. 2004). Slower and less accurate relatedness judgements of more distant concepts with weaker semantic links may result from the need to suppress competitor nodes with stronger semantic links that may be pre-activated when participants see the first word in a pair.

In conclusion, the results of Study 2 showed that semantic processing is modulated by the strength of semantic links between words and that semantic relatedness judgements can be influenced by working memory type and load, but the direction and size of the impact depend on the strength of semantic relations. Study 2 also demonstrated that the semantic relatedness task can be effectively used to investigate the role of executive functions and different types of semantic relations in semantic processing because it requires participants to access meaning of both words in a pair. This task was also used in Study 3 to investigate the processing of word pairs with different types of associations in the native and non-native language.

6.4. Study 3 (Chapter 5) – Relatedness judgements of English word pairs with forward, backward and symmetric association by native and non-native speakers

6.4.1. Summary

Several studies (Thomas et al. 2012; Hutchison et al. 2014; Heyman et al. 2015, 2017) investigated the role of strategic mechanisms in semantic processing using word pairs with different association directions (forward, backward, symmetric). These studies focused on the semantic priming effects in a lexical decision task and were conducted in the participants' native language. Study 2 presented in Chapter 4 and discussed in Section 6.3 demonstrated that the facilitation effects of related versus unrelated pairs can also be observed in the semantic relatedness task, which requires deeper meaning processing and can be effectively used to study semantic processing. Furthermore, as discussed in Section 1.3.4, semantic priming effects have also been reported in the non-native language, but no studies have compared semantic processing of symmetric and asymmetric associates in a semantic relatedness task in the native and non-native language. This gap in research was addressed by Study 3 presented in Chapter 5. Participants in Experiment 3.1 were native English speakers, whereas Experiment 3.2 involved proficient non-native speakers of English. The stimuli were identical in both experiments and included English word pairs with forward, backward or symmetric associations adapted from Thomas et al. (2012). The word pairs were selected by Thomas et al. (2012) based on their associative links. However, it was unclear whether the pairs were also semantically related. To investigate this, the analysis of vector-based semantic similarity values revealed that associatively related pairs were also more strongly related semantically than unrelated pairs. Moreover, symmetric associates showed a higher degree of semantic relatedness than either forward or backward associates.

The first research question focused on the effect of associatively related versus unrelated pairs in the semantic relatedness task in the native language. As was expected, the participants were faster in making decisions about related than unrelated pairs in all conditions. This facilitation effect was the largest for symmetric associates, with the size of the effect equalling the sum of the effects for backward and forward associates.

The differences in relatedness judgements of related versus unrelated pairs between the native and proficient non-native speakers of English were the focus of the second research question. Experiment 3.2 was conducted with proficient non-native speakers of English and revealed a similar pattern of facilitation effects for all types of association to that found with the native English speakers in Experiment 3.1. However, the responses of non-native speakers in the present study were overall significantly slower as compared to native speakers (855 ms vs 669 ms). The between-group comparison of reaction times showed a trend towards a larger facilitation effect in non-native speakers, which was also observed in the reaction time distribution, but the interaction between language group and relatedness was not statistically significant.

The third research question of Study 3 explored the influence of the type of association on relatedness judgements in the native and non-native language. Notably, symmetric (SYM, e.g. *answer – question*) associates showed an additive effect in both groups, i.e. the magnitude of the facilitation effect for SYM pairs was comparable to the sum of facilitation effects for backward (BA, e.g. *ball – catch*) and forward (FA, e.g. *panda – bear*) pairs. Between-group differences in facilitation effects were very similar for all types of associations (Fig. 26 in Section 5.5), but the error analysis revealed that non-native speakers made surprisingly many errors (20.7%) when judging related forward associates (Table 30 in Section 5.4.2). Overall, participants in both language groups were less accurate in their responses to related than to unrelated pairs, but the difference was particularly large for the FA condition in non-native speakers. When items that resulted in the highest error rates in non-native speakers were removed from the analysis in both groups, a similar pattern of results between groups was found, with larger mean reaction times for non-native speakers and with significant facilitation effects for all types of associations in both groups. The main difference in this follow-up analysis was observed for FA and SYM pairs because the facilitation effects in these conditions were larger than in the original analysis for both native and non-native speakers.

6.4.2. Discussion and theoretical implications

The semantic relatedness task proved to be an effective technique for investigating the influence of working memory on semantic processing in Study 2, so the same task was used to explore the role of different strategic processes and asymmetric associative relations in native and non-native language processing in Study 3. Previous studies that focused on asymmetric semantic priming (Thomas et al. 2012; Hutchison et al. 2014; Heyman et al. 2015, 2017) used the lexical decision task and involved only native speakers. However, as was discussed in Section 1.3.4, the facilitation effect of related compared to unrelated pairs has been observed when words in a pair were presented in a non-native language or in different languages known to participants (Altarriba and Basnight-Brown 2009; Basnight-Brown and Altarriba 2007; de Groot and Nas 1991; Duyck 2005; Keatley et al. 1994; Perea et al. 2008; Schoonbaert et al. 2009; Smith et al. 2019; Wen and van Heuven 2017).

The first research question of Study 3 was whether the semantic relatedness task would yield comparable facilitation effects of associatively related pairs in the native language as previous primed lexical decision studies that used very similar materials (Thomas et al. 2012; Hutchison et al. 2014; Heyman et al. 2015, 2017). As was hypothesised, the results of Experiment 3.1 were consistent with previous semantic priming lexical decision studies. Whereas the lexical decision task taps into lexical representations and automatic processes, the semantic relatedness task requires participants to compare the meanings of two words in a pair and make an explicit decision about their relatedness. Despite the differences between the task demands, the findings of Study 3 suggest that the semantic relatedness task, which is less common in semantic processing research (see

Section 1.4), can be used to investigate the spread of activation between words with different types of association. This result is also consistent with Study 2 of this thesis that found a facilitation effect of semantically strongly related pairs relative to unrelated ones in the semantic relatedness task.

The second research question of Study 3 concerned the comparison of facilitation effects between native and proficient non-native speakers of English. Previous studies in the non-native language consistently found a facilitation effect in both lexical decision (Frenck-Mestre and Prince 1997; Phillips et al. 2004; Ankerstein 2014) and semantic relatedness tasks (Thierry and Wu 2007; Wu and Thierry 2010). However, as far as I am aware, there have been no studies directly comparing the performance of native and non-native speakers in a semantic relatedness task. In line with the results of the few previous studies that compared the performance on the lexical decision task in native and non-native groups (Frenck-Mestre and Prince 1997; Ankerstein 2014), proficient non-native speakers in Study 3 were significantly slower at making relatedness judgements than native speakers. Frenck-Mestre and Prince (1997), who used masked priming with a short 67 ms prime duration, argued that the difference in response latency does not necessarily suggest the use of strategic semantic processing, but may reflect slower decision-making in the lexical task in the non-native language. In the present study, however, the stimulus onset asynchrony was 200 ms and the prime was not masked, so participants might have taken advantage of some top-down processes. It is also possible that slower overall reaction times in Experiment 3.2 were due to lower exposure to the words in a non-native language relative to native language (Brysbaert et al. 2018) or a temporal delay in the activation of semantic representations through words in a non-native language (Dijkstra and van Heuven 2002). Also, this difference in responses may potentially result from the demands of the task requiring decision-making.

An alternative explanation of slower responses in the non-native language is related to the findings that the native language can be unconsciously activated during non-native language comprehension (Thierry and Wu 2007; Wu and Thierry 2010; Morford et al. 2011; Zhang et al. 2011; Wen and van Heuven 2018) indicating that the non-native language may not be completely independent from the native language even in proficient bilinguals. It may be assumed that in the explicit semantic task used in this study, non-native speakers accessed semantic representations in the non-native language or even translated the English words into their native language, which resulted in longer reaction times.

In line with Ankerstein (2014), who reported a similar pattern of the priming effect in the lexical decision task for native and non-native speakers, the findings of Study 3 revealed significant facilitation effects in advanced non-native speakers of English that were comparable or even larger in magnitude than those observed with native English speakers. Whereas the mixed-effects model did not reveal a significant difference between groups (although there was such a trend), the delta plot of RT distribution (Fig. 27 in Section 5.5.1) demonstrates that the magnitude of the facilitation effect was larger for non-native speakers throughout the RT range for asymmetric associates and was also larger for symmetric associates in all but the last quantile. This suggests that the processing of semantic relations with words in a non-native language involves the same amount of spreading activation as with words from the first language even though the semantic system is activated through the words in the non-native language. This assumption is also consistent with the models of bilingual processing that include the level of semantic representations and favour language non-selective access, meaning that the processing of words in any language will activate semantic representations in the shared mental lexicon, e.g. BIA+ (Dijkstra and van Heuven 2002) and Multilink (Dijkstra et al. 2019).

The level of language proficiency may also play a crucial role in experiments involving non-native speakers because it is an important factor in the organisation of bilingual semantic memory (de Groot 1995). In Study 3, the LexTALE vocabulary test (Lemhöfer and Broersma 2012) was used to estimate participants' proficiency in English and select advanced non-native speakers. In previous studies, the degree of semantic activation in the non-native language was shown to depend on the level of proficiency (Altarriba and Basnight-Brown 2009; Basnight-Brown and Altarriba 2007; Frenck-Mestre and Prince 1997; Keatley et al. 1994), but in the present study there was no correlation between the LexTALE score and either reaction times ($p = 0.73$) or facilitation effects ($p = 0.52$) in non-native speakers, indicating that the group was homogeneous with regard to their knowledge of English. This is likely because participants in the non-native group were recruited from the senior year of the BA programme or from the MA programme at the Faculty of English at Adam Mickiewicz University in Poznan. All students at this level passed the year-end (BA) or entrance (MA) exams that are equivalent to the C1/C2

CEFR level of proficiency. The LexTALE test was also administered to the native group because many native speakers do not score 100% on this test. Surprisingly, there was a high variability in the test results among native speakers with 14 participants (23%) scoring less than 85%. Although it is unreasonable to discuss the level of native-language proficiency, the results may reflect the level of vocabulary knowledge and possibly also how focused participants were during the test.

The third research question of Study 3 concerned the differences between the processing of BA, FA and SYM pairs in the native and non-native language. The size of the facilitation effect for SYM pairs was equal (native group) or almost equal (non-native group) to the sum of effects for BA and FA pairs. A similar pattern was reported by Thomas et al. (2012) in the lexical decision study conducted in the native language. This finding suggests a convergent impact of prospective and retrospective processes on semantic relatedness judgements, just as on semantic priming effects (Thomas et el. 2012). This result also supports the hypothesis about the additive effect of semantic activation from different sources (Balota and Paul 1996; Thomas et al. 2012). In Study 3, however, the additive effect may also be explained by a significantly higher semantic similarity of related SYM pairs (see Table 26 in Section 5.3.1.3) relative to either FA or BA pairs. It is difficult to disentangle the influence of bidirectional associative and stronger semantic relatedness, so either or both these factors may have contributed to the increased facilitation effect for SYM pairs.

Whereas the facilitation effects for different types of association were similar between the groups, non-native speakers made more errors, especially in the FA condition. Ning et al. (2020) found that high-proficient bilinguals process relatedness differently than monolinguals or low-proficient bilinguals because they develop more links and associations between words in both languages. According to this line of reasoning, it is probable that speakers also form more associations between words in the native than in the non-native language. It is surprising however that this difference concerned only one type of stimuli. It is believed that FA associates rely on the prospective expectancy generation strategies (Hutchison et al. 2014; Neely and Kahan 2001; Thomas et al. 2012). A high error rate in this condition may therefore suggest that non-native speakers had difficulties with pre-activating correct related words or with inhibiting incorrect expectations. In previous studies, it was also forward associates that were found to be modulated by participants’ attentional control abilities (Hutchison et al. 2014) and working memory load (Heyman et al. 2015). Because bilingual language processing requires a high level of monitoring and control (Green 1998; Antón et al. 2019), performing the semantic relatedness task in the non-native language could have taxed the inhibitory resources required for successful proactive strategies. Nonetheless, when non-native speakers made a correct relatedness judgement for FA associates, the facilitation effect was similar for BA associates and was even larger than in the same condition in the native group (Fig. 27 in Section 5.5.1).

An alternative explanation for the high error rate may be related to individual stimuli used in the experiment. When items that resulted in the highest error rates were removed from analysis for both groups, forward associates showed a larger facilitation effect compared to backward associates. Overall, the results of the follow-up analysis suggest that, when only stimuli that elicited consistent responses were taken into consideration, a boost in the facilitation effect for forward and symmetric associates was observed, while the general pattern of results remained similar to the analysis with all items. This finding suggests that prospective anticipatory strategies may play a particularly important role in non-native language processing.

The differences between analyses with and without problematic items lead to a methodological discussion concerning the selection of stimuli in bilingual studies (Altarriba and Basnight-Brown 2007, 2009; de Groot 1995). The stimuli used in the present experiments were previously validated in several monolingual studies on asymmetric semantic priming (Heyman et al. 2017; Hutchison et al. 2014; Thomas et al. 2012). The final set of prime-target pairs was further reduced by eliminating cognates and interlingual homographs because they have been found to affect bilingual language comprehension (Gerard and Scarborough 1989; de Groot and Nas 1991; Poort and Rodd 2019, 2022). Nevertheless, a closer investigation of the stimuli demonstrated that, although they were selected based on associative relatedness, many of them also shared semantic features or categories. In fact, some of word pairs were synonyms (e.g. *end – conclude*) or antonyms (e.g. *wrong – correct*). Moreover, when the lexical characteristics of the stimuli were determined for the final set (Table 26 in Section 5.3.1.3), first words (primes) in FA pairs turned out to have a lower frequency and a higher mean length as compared to other conditions. The original studies (Hutchison et al. 2014; Thomas et al. 2012) reported lexical characteristics only for the target words and not for the primes. These differences between conditions might have also contributed to mixed results for forward associates across the two analyses in the present study. Furthermore, although non-native participants were all proficient users of English, it cannot be ruled out that certain low-frequency words were unfamiliar to some participants (e.g. *quill, shears*).

6.4.3. Limitations and future research

The selection of the experimental stimuli constitutes the main limitation of Study 3. The word pairs were taken from previous studies and adapted for the bilingual setup, but the critical stimulus set may have required more norming to eliminate potential confounding variables and minimise variability across groups and conditions. This is particularly important in relation to non-native speakers because a number of subject- and item-related factors have been found to affect L2 language processing, including but not limited to the level of proficiency, language environment, relationship between bilingual's languages, word frequency and length, and cognate status (de Groot 1995; Altarriba and Basnight-Brown 2007, 2009; Newman et al. 2012; Brysbaert et al. 2018; Poort and Rodd 2019, 2022). Further research into semantic processing with words presented in the native and non-native language will benefit from a better-matched set of linguistic stimuli.

Another limitation of the present study is related to the long-debated dichotomy between associative and semantic relations. Asymmetric associations between words in a pair in the present study were expected to reflect different strategic processes involved in semantic activation. Although it is difficult to separate purely associative from purely semantic relations (Kumar 2021; McNamara 2005), there has been some evidence that more direct associative links are processed differently from more indirect semantic links (Lucas 2000; Perea and Rosa 2002; Hutchison 2003; Ferrand and New 2004). The results indicate that there might be certain differences between native and non-native speakers with regard to prospective strategies involved in the processing of FA and SYM pairs. However, taking into account that this study used a semantic relatedness task requiring participants to explicitly access the meaning of each of the words in the pair, it is difficult to interpret the effect of the type of association between words in a pair because semantic links may have also contributed to the facilitation effects.

Furthermore, previous research has shown that the performance on language tasks may depend on individual variations in executive functions, such as inhibition, attentional control, and working memory capacity (Daneman and Carpenter 1980; Gathercole 2007; Hutchison et al. 2014; Radel et al. 2015). At the same time, there is a debate about the potential impact of knowing several languages on domain-general skills (Bialystok et al. 2008; Grundy and Timmer 2017; Lehtonen et al. 2018; Antón et al. 2019). Therefore, information about the participants' baseline level of working memory capacity or attentional control in additional to the level of proficiency might have been useful to explain performance on the semantic relatedness task. Future research might benefit from accounting for the role of individual differences in semantic processing.

Finally, a prospective avenue of research concerns the role of working memory and other executive functions on semantic processing in a non-native language. Study 2 demonstrated that semantic processing in the native language is affected by working memory load. Study 3 showed that the facilitation effect of related word pairs is reliably observed in the non-native language but may be affected by specific strategies adopted by non-native speakers and be modulated by the type of association between words. To the best of my knowledge, no studies have yet compared the effects of working memory load or other executive functions on semantic processing with words in the native versus non-native language, or among bilinguals versus monolinguals.

6.4.4. Conclusions

Study 3 investigated the semantic processing of word pairs with forward, backward and symmetric association in the semantic relatedness task in the native and non-native language. Importantly, although non-native speakers were overall significantly slower at making relatedness judgements, a facilitation effect of related pairs was found for all types of association and was similar in size for native and proficient non-native speakers of English. The results indicate that the spread of semantic activation in the semantic relatedness task is similar when words are presented in the native or non-native language and is comparable to previous studies that used the lexical decision task in native speakers (Thomas et al. 2012; Hutchison et al. 2014; Heyman et al. 2015, 2017). Non-native speakers may however be slower at activating the semantic system because of the need to access the semantics through words in a non-native language or because of specific strategies involved in non-native language processing. Importantly, symmetric associates resulted in the largest facilitation effects in both groups indicating additive effects from prospective and retrospective strategies involved in semantic processing and from the overlap of associative and semantic links in symmetric pairs. Furthermore, non-native speakers were significantly less accurate at judging the relatedness of pairs with forward association, which may suggest that prospective strategies may be particularly important in the processing of the non-native language.

6.5. Final remarks

The experimental studies reported in this doctoral thesis provide important insights into the structure of semantic memory with a particular focus on the role of working memory and different types of semantic relations in semantic processing in the native and non-native language.

One of the key findings of this thesis is that semantic processing can be influenced by the type and extent of concurrent working memory load. The direction and size of this influence is also dependent on the strength of semantic relations between words. A series of experiments with the semantic relatedness task (Study 2 reported in Chapter 4) demonstrated that decisions about the relatedness of two words in a pair were faster when target words were preceded by semantically strongly related words but slower when preceded by semantically weakly related words relative to unrelated words. Additional verbal working memory demands reduced the facilitatory effect for strongly related pairs and increased the inhibitory effect for weakly related pairs, compared to spatial working memory demands. Semantically weakly related pairs were particularly sensitive to working memory load. Overall, the findings support the view that semantic processing can be modulated by high-level cognitive functions (Hutchison et al. 2014; Heyman et al. 2015; Radel et al. 2015). The results are also consistent with the assumption of the functional separability of spatial and verbal working memory resources (Baddeley et al. 2020; Shah and Miyake 1996) and demonstrate that domain-specific working memory load may impact semantic processing. Furthermore, these findings contribute to the spreading activation theory of semantic memory (Collins and Loftus 1975) with regard to the role of the strength of semantic relations in semantic processing.

The nature of relations between word pairs published by Rataj et al. (2023) and used for the above working memory study was verified in a free word association experiment (Study 1 presented in Chapter 3) that followed the network-based models of semantic memory (Steyvers and Tenenbaum 2005; De Deyne and Storms 2008; DeDeyne et al. 2019). Importantly, the results provided evidence that the word pairs were mostly related semantically rather than associatively. This finding corroborates previous findings suggesting a distinction between word-based associative relations and meaning-based semantic relations (Lucas 2000; Perea and Rosa 2002; Hutchison 2003; Ferrand and New 2004; McRae et al. 2012; Vivas et al. 2019; Kumar 2021). Additionally, Study 1 compared associative norms from human responses with the vector-based measure of semantic similarity (Mykowiecka et al. 2017; Rataj et al. 2023), taking advantage of the recent prediction-based computational models of semantic memory (Mikolov et al. 2013; Günther et al. 2019; Kumar 2021). The associations database developed in Study 1 can be of practical value for further research taking into account that there is limited association data available for the Polish language.

Other evidence for the role of different types of relations between words in semantic processing comes from Study 3 (Chapter 5) that focused on semantic relatedness judgements in the native and non-native language. Regardless of the language status, a facilitation effect of related versus unrelated word pairs was found for forward, backward and symmetric associates, with the largest effect for the latter. These results were consistent with previous primed lexical decision studies that investigated symmetric and asymmetric associations in the native language (Thomas et al. 2012; Hutchison et al. 2014; Heyman et al. 2015, 2017). The data also demonstrated that participants may resort to different strategies when making relatedness decisions in a non-native as compared to native language although semantic activation mechanisms were similar regardless of whether the words were presented in the native or non-native language. These findings are consistent with previous research that compared semantic processing between native and non-native speakers (Frenck-Mestre and Prince 1997; Phillips et al. 2004; Ankerstein 2014) and contribute to the understanding of the organisation of bilingual semantic memory.

Another important contribution of the thesis to the literature is related to the task used to explore semantic processing in Studies 2 and 3. Whereas most previous studies in the field investigated semantic processing using the semantic priming paradigm in a lexical decision task, the semantic relatedness task was used in this thesis because it involves deeper semantic processing of both words in a pair and more closely resembles natural language processing. Whereas the lexical decision task is commonly used for investigating automatic processes and lexical representations, the semantic relatedness task can be effectively used to explore strategic processing at the semantic level.

Conclusions

The study of word meaning and factors influencing meaning processing has been in the focus of lexical semantics research for the past several decades. With the growing empirical evidence and the emergence of new theoretical models, our understanding of how word meaning is formed and retrieved from memory has developed significantly. Although conceptual meaning representations are not directly accessible, language reflects complex relations between objects and ideas in the outside world and is a powerful tool for indirectly investigating meaning representations. By studying the influence of different factors on language processing, it is therefore possible to make inferences about the mechanisms involved in semantic processing. This thesis encompassed three experimental studies whose main objective was to explore the mechanisms involved in the processing of different types of semantic relations in the native and non-native language, with a special focus on the role of working memory in semantic processing.

The main finding of Study 1 (Chapter 3) was that most of the Polish word pairs from the tested dataset (Rataj et al. 2023) were related semantically rather than associatively. It was important to investigate the nature of relations in the stimulus set because it was used later in the project in a semantic relatedness study. There is evidence from the literature pointing to differences in the processing of associative and semantic relations (Lucas 2000; Perea and Rosa 2002; Hutchison 2003; Ferrand and New 2004; McRae et al. 2012; Vivas et al. 2019; Kumar 2021), but the Polish word pairs had not been previously tested for associative relations. A free word association experiment involving 484 native Polish speakers was conducted to establish association norms for the tested dataset. The theoretical framework for Study 1 was based on two approaches to the study of semantic memory. On the one hand, network-based models (Collins and Loftus 1975; De Deyne et al. 2016) represent concepts as interconnected nodes, and the nature of relations between the nodes is dependent on our linguistic or general-world experience. On the other hand, recent computational models postulate that meanings and semantic relations can be inferred from the patterns of word co-occurrences in large collections of texts (Landauer and Dumais 1997; Mikolov et al. 2013; Baroni et al. 2014; Günther et al. 2019; Kumar 2021). Study 1 linked these two approaches together by showing that association measures obtained from participants correlated with semantic similarity measures obtained from semantic spaces (Mykowiecka et al. 2017; Rataj et al. 2023). Study 1 also holds practical significance because association norms were developed and for the first time compared against vector-based similarity measures for a relatively large set of words in the Polish language, which is often underrepresented in psycholinguistic studies.

The relations between meaning representations are often investigated in studies involving word pairs with a different degree of relatedness because qualitative and quantitative differences are usually found between the processing of related and unrelated word pairs. The semantic relatedness task was used in Study 2 (Chapter 5) to investigate for the first time whether additional working memory in the spatial and verbal domains affects semantic relatedness judgements of semantically strongly and weakly related pairs of words. Crucial findings indicated that working memory type and load influenced semantic relatedness judgements but that the direction and size of the impact depended on the strength of semantic relations. These results provided support for the assumptions concerning mutual dependency between semantic processing and general cognitive functions (Neely 1991; Neely and Kahan 2001; Thomas et al. 2012; Hutchison et al. 2014; Heyman et al. 2015; Radel et al. 2015). Importantly, verbal working memory load had a stronger effect on semantic processing than spatial working memory load, providing evidence for domain specificity of working memory (Shah and Miyake 1996; Nagel et al. 2007; Zhao et al. 2010; Clouter et al. 2015; Swanson 2017). This finding is also consistent with the multicomponent model of working memory (Baddeley and Hitch 1974; Baddeley 2000, 2011, 2021; Baddeley et al. 2020) distinguishing between different resources for the processing of verbal and spatial information.

One of Study 2's distinctive features was that it treated semantic relatedness as a continuous rather than a binary value by including an intermediate condition of weakly related pairs (see Rataj et al. 2023). The results indicated that target words preceded by weakly related words were recognised slower than those preceded by either strongly related or unrelated words. This inhibition effect was independent of the experimental procedure but was significantly enhanced by high verbal working memory load. These findings suggest that weak semantic links are particularly sensitive to executive demands and that the strength of semantic relations is an important factor that should be taken into account in further research. It was proposed that the inhibition effect for semantically weakly related pairs may be due to the need to suppress competitor concepts with stronger semantic links than the target. This assumption has implications for the spreading activation theory of semantic processing (Collins and Loftus 1975) and the activation-suppression hypothesis (De Jong et al. 1994; Burle et al. 2002; Ridderinkhof et al. 2004).

Important questions are whether the mechanisms of semantic processing are similar in the native and non-native language and whether non-native language processing involves certain strategic processes that differ from the native language. These questions were the focus of two experiments in Study 3 (Chapter 5) that involved native and proficient non-native speakers of English. The results of this study revealed significant facilitation effects of related pairs for both native and proficient non-native speakers of English indicating that similar spreading activation mechanisms may be in place in the first and second language. However, non-native speakers took significantly longer to make semantic relatedness decisions and showed a different pattern of results for word pairs with forward association. This provides evidence that semantic processing of words in a non-native language may involve different strategic processes as compared to the native language.

A novel feature of the experiments conducted in Studies 2 and 3 was the use of the semantic relatedness judgement task for the investigation of semantic processing. Although most previous studies in the field used the semantic priming lexical decision task that focuses on lexical representations, the experiments presented in this thesis suggest that the relatedness judgement task is a valid method for studying semantic representations. Moreover, it may have advantages over the lexical decision task for research questions involving working memory and strategic processing because it requires participants to focus on the semantics of both words in the presented pairs.

In conclusion, the findings reported in this thesis contribute to our understanding of semantic memory and the role of different types of semantic relations and strategic processes in semantic processing with words of the native and non-native language.

Furthermore, the results have methodological implications related to the use of the semantic relatedness task for investigating semantic processing as well as practical implications for future research into the influence of executive functions and semantic relations on semantic processing in the native and non-native language.

Abstract

Words are basic meaningful elements of every language, and how their meanings are processed and retrieved from memory has been a subject of extensive psycholinguistic and cognitive research for the last several decades. The evolution of theoretical accounts of semantic memory (Smith et al. 1974; Collins and Loftus 1975; Tversky 1977; Lund and Burgess 1996; Landauer and Dumais 1997; McRae 2004; De Deyne and Storms 2008; Vigliocco et al. 2009; Mikolov et al. 2013; De Deyne et al. 2016; Kumar 2021) and a large body of empirical evidence have advanced our understanding of relations between language and cognition. However, there are gaps in lexical semantics research related to the role of working memory and different types of semantic relations in semantic processing in the native and non-native language. This thesis encompasses three experimental studies aiming to address these gaps.

In Study 1, associative norms were established for a set of Polish words (Rataj et al. 2023) in a free word association experiment involving 484 native Polish speakers. These words had previously been tested for semantic but not associative relatedness. The key research question of Study 1 was whether semantically related words from a semantic priming dataset were also related associatively. Importantly, the results demonstrated that semantically related word pairs from the tested dataset are minimally associated. This provided crucial evidence that the tested dataset can be used to investigate the influence of various factors specifically on the processing of semantic relations. The practical value of Study 1 was that association norms were developed and for the first time compared against vector-based similarity measures (Mykowiecka et al. 2017; Rataj et al. 2023) for

a relatively large set of words in the Polish language, which is often underrepresented in psycholinguistic studies.

The dataset tested in Study 1 was further used in Study 2, which aimed to investigate whether high and low working memory load in the verbal and spatial domain would impact the processing of word pairs with different degrees of semantic relatedness. Previous studies focused either on relatedness judgements (Kuperberg et al. 2008; Ortu et al. 2013) or on the impact of working memory load on semantic processing (Heyman et al. 2015, 2017), but the differences in the influence of verbal and spatial working memory load on relatedness judgements were investigated for the first time in Study 2. A series of experiments with the semantic relatedness task provided evidence that semantic relatedness judgements were faster when target words were preceded by strongly related words but slower when preceded by weakly related words relative to unrelated words. These effects were modulated by the type and extent of working memory load, with additional verbal working memory demands having a stronger influence on relatedness judgements as compared to spatial working memory. This indicates that semantic processing of words in the semantic relatedness task can be affected by the availability of verbal working memory resources and by the degree of semantic relatedness between words.

Further evidence for the role of different types of relations in semantic processing was presented in Study 3 that explored for the first time semantic relatedness judgements of word pairs with asymmetric and symmetric association in the native and non-native language. The results of this study revealed significant facilitation effects of related pairs for both native and proficient non-native speakers of English indicating that similar spreading activation mechanisms may be in place in the first and second language. It was also found that semantic processing in a non-native language may involve different strategic processes as compared to the native language.

In conclusion, the findings reported in this thesis contribute to our understanding of semantic memory and the role of different types of semantic relations and different strategic mechanisms in semantic processing in the native and non-native language. Furthermore, they have important methodological and empirical implications for future research into the role of working memory and different types of semantic relations in semantic processing.

Streszczenie

Słowa są podstawowymi znaczącymi elementami każdego języka, a sposób, w jaki ich znaczenia są przetwarzane i odzyskiwane z pamięci, stanowi przedmiot intensywnych badań psycholingwistycznych i kognitywnych od ostatnich kilku dekad. Ewolucja teoretycznych modeli pamięci semantycznej (Smith et al. 1974; Collins and Loftus 1975; Tversky 1977; Lund and Burgess 1996; Landauer and Dumais 1997; McRae 2004; De Deyne and Storms 2008; Vigliocco et al. 2009; Mikolov et al. 2013; De Deyne et al. 2016; Kumar 2021) oraz liczne dowody empiryczne przyczyniły się do lepszego zrozumienia relacji między językiem a systemem poznawczym. W badaniach semantyki leksykalnej istnieją jednak luki związane z rolą jaką pamięć robocza i różne rodzaje relacji semantycznych odgrywają w przetwarzaniu semantycznym w języku rodzimym i obcym. Niniejsza rozprawa obejmuje trzy badania eksperymentalne mające na celu uzupełnienie tych luk.

W Badaniu 1 ustalono normy skojarzeniowe dla zestawu polskich słów (Rataj et al. 2023) w eksperymencie swobodnych skojarzeń słownych z udziałem 484 rodzimych użytkowników języka polskiego. Słowa te były wcześniej testowane pod kątem pokrewieństwa semantycznego, ale nie skojarzeniowego. Kluczowym pytaniem badawczym było to, czy semantycznie powiązane słowa ze zbioru słów wykorzystanych do badania poprzedzania semantycznego były również powiązane skojarzeniowo. Co ważne, wyniki wykazały, że semantycznie powiązane pary słów z testowanego zbioru są minimalnie powiązane skojarzeniowo. Wyniki te dostarczyły kluczowych dowodów na to, że testowany zestaw słów może być wykorzystywany do badania wpływu różnych czynników na przetwarzanie relacji semantycznych. Praktyczna wartość Badania 1 polegała na tym, że

opracowano normy skojarzeniowe i po raz pierwszy porównano je z miarami podobieństwa opartymi na wektorach (Mykowiecka et al. 2017; Rataj et al. 2023) dla stosunkowo dużego zbioru słów w języku polskim, który jest często niedostatecznie reprezentowany w badaniach psycholingwistycznych.

Zbiór słów przetestowany w Badaniu 1 został następnie wykorzystany w Badaniu 2, którego celem było zbadanie, czy duże i małe obciążenie werbalnej i przestrzennej pamięci roboczej wpłynie na przetwarzanie par słów o różnym stopniu pokrewieństwa semantycznego. Wcześniejsze badania koncentrowały się albo na ocenach powiązań semantycznych (Kuperberg et al. 2008; Ortu et al. 2013), albo na wpływie obciążenia pamięci roboczej na przetwarzanie semantyczne (Heyman et al. 2015, 2017), ale różnice we wpływie obciążenia werbalnej i przestrzennej pamięci roboczej na oceny powiązań semantycznych zostały zbadane po raz pierwszy w Badaniu 2. Seria eksperymentów z zadaniem polegającym na określeniu powiązań semantycznych dostarczyła dowodów na to, że ocena ta była szybsza, gdy słowa docelowe były poprzedzone ściśle powiązanymi słowami, ale wolniejsza, gdy poprzedzały je słowa słabo powiązane w stosunku do słów niepowiązanych. Efekty te były modulowane przez typ i stopień obciążenia pamięci roboczej, przy czym dodatkowe obciążenie werbalnej pamięci roboczej miało silniejszy wpływ na oceny pokrewieństwa w porównaniu z obciążeniem pamięci roboczej przestrzennej. Wskazuje to, że na przetwarzanie semantyczne słów w zadaniu polegającym na ocenie powiązań semantycznych może wpływać dostępność zasobów werbalnej pamięci roboczej oraz stopień pokrewieństwa semantycznego między słowami.

Dalsze dowody na rolę różnych typów powiązań w przetwarzaniu semantycznym dostarczono w Badaniu 3, które po raz pierwszy skupiło się na ocenie powiązań semantycznych par słów z asymetrycznymi oraz symetrycznymi powiązaniami skojarzeniowymi w języku rodzimym i obcym. Wyniki tego badania ujawniły znaczące efekty facylitacji dla powiązanych par słów w porównaniu z niepowiązanymi parami zarówno dla rodzimych, jak i biegłych nierodzimych użytkowników języka angielskiego, wskazując na obecność podobnych mechanizmów rozprzestrzeniającej się aktywacji w pierwszym i drugim języku. Stwierdzono również, że przetwarzanie semantyczne w języku obcym może obejmować inne procesy strategiczne w porównaniu z językiem ojczystym.

Podsumowując, wyniki przedstawione w niniejszej rozprawie przyczyniają się do lepszego zrozumienia pamięci semantycznej oraz roli różnych typów powiązań semantycznych i różnych mechanizmów strategicznych w przetwarzaniu semantycznym w języku rodzimym i obcym. Ponadto niosą one ważne implikacje metodologiczne i empiryczne dla przyszłych badań nad rolą pamięci roboczej i różnych rodzajów powiązań semantycznych w przetwarzaniu znaczenia.

References

Adams, Eryn J., Anh T. Nguyen and Nelson Cowan. 2018. “Theories of working memory: Differences in definition, degree of modularity, role of attention, and purpose”, *Language, Speech, and Hearing Services in Schools* 49, 3: 340-355.

Altarriba, Jeanette and Dana M. Basnight-Brown. 2007. “Methodological considerations in performing semantic- and translation-priming experiments across languages”, *Behavior Research Methods* 39: 1-18.

Altarriba, Jeanette and Dana M. Basnight-Brown. 2009. “An overview of semantic processing in bilinguals: Methods and findings”, in: Aneta Pavlenko (ed.), *The bilingual mental lexicon: Interdisciplinary approaches*. Bristol, Blue Ridge Summit: Multilingual Matters, 79-98.

Altarriba, Jeanette and Ludmila Isurin (eds.). 2012. *Memory, Language, and Bilingualism: Theoretical and Applied Approaches*. Cambridge: Cambridge University Press.

Amunts, Julia, Julia A. Camilleri, Simon B. Eickhoff, Stefan Heim and Susanne Weis. 2020. “Executive functions predict verbal fluency scores in healthy participants”, *Scientific Reports* 10, 1: 11141.

Anderson, Jane E. and Phillip J. Holcomb. 1995. “Auditory and visual semantic priming using different stimulus onset asynchronies: An event-related brain potential study”, *Psychophysiology* 32, 2: 177-190.

Ankerstein, Carrie A. 2014. “A psycholinguistic measurement of second language proficiency: The coefficient of variation”, in: Pascale Leclercq, Amanda Edmonds and Heather Hilton (eds.), *Measuring L2 Proficiency: Perspectives from SLA*. Bristol, Blue Ridge Summit: Multilingual Matters, 109-121.

Antón, E., M. Carreiras and J. A. Duñabeitia. 2019. “The impact of bilingualism on executive functions and working memory in young adults”, *PLOS ONE* 14, 2: e0206770.

Archibald, Lisa M. D. 2017. “Working memory and language learning: A review”, *Child Language Teaching and Therapy* 33, 1: 5-17.

Baddeley, Alan D. 2000. “The episodic buffer: A new component of working memory?”, *Trends in Cognitive Sciences* 4, 11: 417-423.

Baddeley, Alan D. 2003. “Working memory and language: An overview”, *Journal of Communication Disorders* 36, 3: 189-208.

Baddeley, Alan D. 2012. “Working memory: Theories, models, and controversies”, *Annual review of psychology*, 63: 1-29.

Baddeley, Alan D. 2021. “Developing the concept of working memory: The role of neuropsychology”, *Archives of Clinical Neuropsychology* 36, 6: 861-873.

Baddeley, Alan D. and Graham Hitch. 1974. “Working memory”, in: Gordon H. Bower (ed.), *Psychology of Learning and Motivation*. Academic Press, 47-89.

Baddeley, Alan D., Richard J. Allen and Graham J. Hitch. 2011. “Binding in visual working memory: The role of the episodic buffer”, *Neuropsychologia* 49, 6: 1393-1400.

Baddeley, Alan D., Susan Gathercole and Costanza Papagno. 1998. “The phonological loop as a language learning device”, *Psychological Review* 105, 1: 158-173.

Baddeley, Alan D., Graham Hitch and Richard Allen. 2020. “A multicomponent model of working memory”, in: Robert Logie, Valerie Camos and Nelson Cowan (eds.), *Working Memory: State of the science*. Oxford: Oxford University Press, 10-43.

Baddeley, Alan D., S. Grant, E. Wight and Neil Thomson. 1973. “Imagery and visual working memory”, in: P. M. A. Rabbitt and S. Dornic (eds.), *Attention and Performance V*. Academic Press, 205-217.

Baddeley, Alan D., Neil Thomson and Mary Buchanan. 1975. “Word length and the structure of short-term memory”, *Journal of Verbal Learning & Verbal Behavior* 14, 6: 575-589.

Balota, David A. and R. F. Lorch. 1986. “Depth of automatic spreading activation: Mediated priming effects in pronunciation but not in lexical decision”, *Journal of Experimental Psychology: Learning, Memory & Cognition* 12: 336-345.

Balota, David A. and Stephen T. Paul. 1996. “Summation of activation: Evidence from multiple primes that converge and diverge within semantic memory”, *Journal of Experimental Psychology: Learning, Memory, and Cognition* 22: 827-845.

Balota, David A., Melvin J. Yap, Keith A. Hutchison, Michael J. Cortese, Brett Kessler, Bjorn Loftis, James H. Neely, Douglas L. Nelson, Greg B. Simpson and Rebecca Treiman. 2007. “The English Lexicon Project”, *Behavior Research Methods* 39, 3: 445-459.

Baqués, Josep, Dolors Sáiz and Jeffrey Bowers. 2004. “Effects of working memory load on long-term word priming”, *Memory* 12, 3: 301-313.

Barabási, Albert-László and Réka Albert. 1999. “Emergence of scaling in random networks”, *Science* 286, 5439: 509-512.

Baroni, Marco, Georgiana Dinu and Germán Kruszewski. 2014. “Don’t count, predict! A systematic comparison of context-counting vs. context-predicting semantic vectors”, in: *Proceedings of the 52nd Annual Meeting of the Association for Computational Linguistics (Volume 1: Long Papers)*. Baltimore, Maryland: Association for Computational Linguistics, 238-247.

Barrouillet, Pierre and Valérie Camos. 2007. “The time-based resource-sharing model of working memory”, in: Naoyuki Osaka, Robert H. Logie and Mark D’Esposito (eds.), *The Cognitive Neuroscience of Working Memory*. Oxford University Press, 59-80.

Barrouillet, Pierre and Valérie Camos. 2020. “The time-based resource-sharing model of working memory”, in: Robert Logie, Valerie Camos and Nelson Cowan (eds.), *Working Memory: State of the science*. Oxford: Oxford University Press, 85-115.

Basnight-Brown, Dana M. and Jeanette Altarriba. 2007. “Differences in semantic and translation priming across languages: The role of language direction and language dominance”, *Memory & Cognition* 35, 5: 953-965.

Bates, Douglas, Martin Mächler, Ben Bolker and Steve Walker. 2015. “Fitting linear mixed-effects models using lme4”, *Journal of Statistical Software* 67: 1-48.

Becker, C. A. 1980. “Semantic context effects in visual word recognition: An analysis of semantic strategies”, *Memory & Cognition* 8: 493-512.

Bentin, Shlomo, Marta Kutas and Steven A. Hillyard. 1995. “Semantic processing and memory for attended and unattended words in dichotic listening: Behavioral and electrophysiological evidence”, *Journal of Experimental Psychology: Human Perception and Performance* 21: 54-67.

Bialystok, Ellen. 2009. “Bilingualism: The good, the bad, and the indifferent”, *Bilingualism: Language and Cognition* 12, 1: 3-11.

Bialystok, Ellen, Fergus I. M. Craik and G. Luk. 2012. “Bilingualism: Consequences for mind and brain”, *Trends in Cognitive Sciences* 16, 4: 240-250.

Biedroń, Adriana and Anna Szczepaniak. 2012. “Working memory and short-term memory abilities in accomplished multilinguals”, *The Modern Language Journal* 96, 2: 290-306.

Bleckley, M. Kathryn, Jeffrey L. Foster and Randall W. Engle. 2015. “Working memory capacity accounts for the ability to switch between object-based and location-based allocation of visual attention”, *Memory & Cognition* 43, 3: 379-388.

Borowsky, Ron and Derek Besner. 2006. “Parallel distributed processing and lexical-semantic effects in visual word recognition: Are a few stages necessary?”, *Psychological Review* 113, 1: 181-193.

Bridges, David, Alain Pitiot, Michael R. MacAskill and Jonathan W. Peirce. 2020. “The timing mega-study: Comparing a range of experiment generators, both lab-based and online”, *PeerJ* 8: e9414.

Brysbaert, Marc, Paweł Mandera and Emmanuel Keuleers. 2018. “The word frequency effect in word processing: An updated review”, *Current Directions in Psychological Science* 27, 1: 45-50.

Brysbaert, Marc and Michaël Stevens. 2018. “Power analysis and effect size in mixed effects models: A tutorial”, *Journal of Cognition* 1, 1: 9.

Burgoyne, Alexander P., Cody A. Mashburn, Jason S. Tsukahara, David Z. Hambrick and Randall W. Engle. 2021. “Understanding the relationship between rationality and intelligence: a latent-variable approach”, *Thinking & Reasoning* 29, 1: 1-42.

Burle, Borís, Camille-Aimé Possamaï, Franck Vidal, Michel Bonnet and Thierry Hasbroucq. 2002. “Executive control in the Simon effect: An electromyographic and distributional analysis”, *Psychological Research* 66, 4: 324-336.

Cabana, Álvaro, Camila Zugarramurdi, Juan C. Valle-Lisboa and Simon De Deyne. 2023. “The ‘Small World of Words’ free association norms for Rioplatense Spanish”, *Behavior Research Methods*.

Caplan, David and Gloria S. Waters. 2005. “The relationship between age, processing speed, working memory capacity, and language comprehension”, *Memory* 13, 3-4: 403-413.

Chai, Wen Jia, Aini Ismafairus Abd Hamid and Jafri Malin Abdullah. 2018. “Working memory from the psychological and neurosciences perspectives: A review”, *Frontiers in Psychology* 9: 401.

Clouter, Andrew, Ryan Wilson, Stefan Allen, Raymond M. Klein and Gail A. Eskes. 2015. “The influence of verbal and spatial working memory load on the time course of the Simon effect”, *Journal of Experimental Psychology: Human Perception and Performance* 41, 2: 342-355.

Colflesh, Gregory J. H. and Andrew R. A. Conway. 2007. “Individual differences in working memory capacity and divided attention in dichotic listening”, *Psychonomic Bulletin & Review* 14, 4: 699-703.

Collins, Allan M. and Elizabeth F. Loftus. 1975. “A spreading-activation theory of semantic processing”, *Psychological Review* 82: 407-428.

Collins, Allan M. and M. Ross Quillian. 1969. “Retrieval time from semantic memory”, *Journal of Verbal Learning and Verbal Behavior* 8, 2: 240-247.

Conrad, R. and A. J. Hull. 1964. “Information, acoustic confusion, and memory span”, *British Journal of Psychology* 55: 429-432.

Conway, Andrew R. A., Michael J. Kane, Michael F. Bunting, D. Zach Hambrick, Oliver Wilhelm and Randall W. Engle. 2005. “Working memory span tasks: A methodological review and user’s guide”, *Psychonomic Bulletin & Review* 12, 5: 769-786.

Cowan, Nelson. 1988. “Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information-processing system”, *Psychological Bulletin* 104, 2: 163-191.

Cowan, Nelson. 1999. “An embedded-processes model of working memory”, in: Akira Miyake and Priti Shah (eds.), *Models of Working Memory*. Cambridge University Press, 62-101.

Cowan, Nelson. 2008. “What are the differences between long-term, short-term, and working memory?”, *Progress in Brain Research* 169: 323-338.

Cowan, Nelson. 2010. “The magical mystery four: How is working memory capacity limited, and why?”, *Current Directions in Psychological Science* 19, 1: 51-57.

Cowan, Nelson, Candice C. Morey and Moshe Naveh-Benjamin. 2020. “An embedded-processes approach to working memory: How is it distinct from other approaches, and to what ends?”, in: Robert Logie, Valerie Camos and Nelson Cowan (eds.), *Working Memory: State of the science*. Oxford: Oxford University Press, 44-84.

Cree, George S. and Ken McRae. 2003. “Analyzing the factors underlying the structure and computation of the meaning of chipmunk, cherry, chisel, cheese, and cello (and many other such concrete nouns)”, *Journal of Experimental Psychology. General* 132, 2: 163-201.

Daneman, Meredyth and Patricia A. Carpenter. 1980. “Individual differences in working memory and reading”, *Journal of Verbal Learning and Verbal Behavior* 19, 4: 450-466.

De Deyne, Simon, Daniel J. Navarro, Amy Perfors and Gert Storms. 2016. “Structure at every scale: A semantic network account of the similarities between unrelated concepts”, *Journal of Experimental Psychology. General* 145, 9: 1228-1254.

De Deyne, Simon, Daniel J. Navarro and Gert Storms. 2013. “Better explanations of lexical and semantic cognition using networks derived from continued rather than single-word associations”, *Behavior Research Methods* 45, 2: 480-498.

De Deyne, Simon, Danielle J. Navarro, Amy Perfors, Marc Brysbaert and Gert Storms. 2019. “The ‘Small World of Words’ English word association norms for over 12,000 cue words”, *Behavior Research Methods* 51, 3: 987-1006.

De Deyne, Simon and Gert Storms. 2008. “Word associations: Network and semantic properties”, *Behavior Research Methods* 40: 213-231.

De Jong, Ritske, Chia-Chin Liang and Erick Lauber. 1994. “Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence”, *Journal of Experimental Psychology: Human Perception and Performance* 20, 4: 731-750.

Diamond, Adele. 2013. “Executive Functions”, *Annual Review of Psychology* 64, 1: 135-168.

Dijkstra, Ton and Walter J. B. van Heuven. 2002. “The architecture of the bilingual word recognition system: From identification to decision”, *Bilingualism: Language and Cognition* 5: 175-197.

Dijkstra, Ton, A. Wahl, F. Buytenhuijs, N. Van Halem, Z. Al-Jibouri, M. De Korte and S. Rekké. 2019. "Multilink: A computational model for bilingual word recognition and word translation", *Bilingualism: Language and Cognition* 22, 4: 657-679.

Donolato, Enrica, David Giofrè and Irene C. Mammarella. 2017. "Differences in verbal and visuospatial forward and backward order recall: A review of the literature", *Frontiers in Psychology* 8: 663.

Duyck, Wouter. 2005. "Translation and associative priming with cross-lingual pseudohomophones: Evidence for nonselective phonological activation in bilinguals", *Journal of Experimental Psychology: Learning, Memory, and Cognition* 31, 6: 1340-1359.

Ellinghaus, Ruben and Jeff Miller. 2018. "Delta plots with negative-going slopes as a potential marker of decreasing response activation in masked semantic priming", *Psychological Research* 82, 3: 590-599.

Engle, Randall W. 2002. "Working memory capacity as executive attention", *Current Directions in Psychological Science* 11, 1: 19-23.

Engle, Randall W and Michael J Kane. 2003. "Executive attention, working memory capacity, and a two-factor theory of cognitive control", *Psychology of Learning and Motivation* 44: 145-199.

Engle, Randall W., Stephen W. Tuholski, James E. Laughlin and Andrew R. A. Conway. 1999. "Working memory, short-term memory, and general fluid intelligence: A latent-variable approach", *Journal of Experimental Psychology: General* 128, 3: 309-331.

Eurostat. 2018. "65% know at least one foreign language in the EU", 26 Sep. 2018. (https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20180926-1) (date of access: 25 Mar. 2023).

Eurostat. 2022. "Foreign language learning statistics", June 2022. (https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Foreign_language_learning_statistics) (date of access: 25 Mar. 2023).

Farah, M. J. and J. L. McClelland. 1991. "A computational model of semantic memory impairment: Modality specificity and emergent category specificity", *Journal of Experimental Psychology. General* 120, 4: 339-357.

Faust, Miriam and Michal Lavidor. 2003. “Semantically convergent and semantically divergent priming in the cerebral hemispheres: Lexical decision and semantic judgment”, *Cognitive Brain Research* 17, 3: 585-597.

Fernández, Sergio, Juan José Ortells, Markus Kiefer, Carmen Noguera and Jan W. De Fockert. 2021. “Working memory capacity modulates expectancy-based strategic processing: Behavioral and electrophysiological evidence”, *Biological Psychology* 159: 108023.

Ferrand, L. and B. New. 2004. “Semantic and associative priming in the mental lexicon”, in: P. Bonin (ed.), *Mental lexicon: “Some words to talk about words”.* Nova Science Publishers, 25-43.

Fiacconi, Chris M. 2023. *Lab tutorial 4: Linear contrasts, trend analysis and focused tests*. (https://cfiaccon.github.io/Lab_Tutorial_4.pdf) (date of access: 29 May 2023)

John Fox and Sanford Weisberg. 2019. *An R companion to applied regression, third edition*. Thousand Oaks CA: Sage. (https://socialsciences.mcmaster.ca/jfox/Books/Companion/) (date of access: 29 May 2023).

Frenck-Mestre, C. and P. Prince. 1997. “Second language autonomy”, *Journal of Memory and Language* 37, 4: 481-501.

Friedman, Naomi P. and Akira Miyake. 2017. “Unity and diversity of executive functions: Individual differences as a window on cognitive structure”, *Cortex* 86: 186-204.

Gao, Quanying, Zhe Chen and Paul Russell. 2007. “Working memory load and the Stroop interference effect”, 36, 3: 146-153.

Gathercole, Susan E. 2007. “Working memory and language”, in: M. Gareth Gaskell (ed.), *The Oxford Handbook of Psycholinguistics*. Oxford University Press, 756-770.

Gathercole, Susan E. and Alan D. Baddeley. 1990. “The role of phonological memory in vocabulary acquisition: A study of young children learning new names”, *British Journal of Psychology* 81, 4: 439-454.

Gathercole, Susan E. and Alan D. Baddeley. 1993. *Working memory and language*. Psychology Press.

Gathercole, Susan Elizabeth, Tracy Packiam Alloway, Catherine Willis and Anne-Marie Adams. 2006. “Working memory in children with reading disabilities”, *Journal of Experimental Child Psychology* 93, 3: 265-281.

Gatkowska, Izabela. 2015. “Empiryczna sieć powiązań leksykalnych”, *Polonica* 35: 155-178.

Gatkowska, Izabela. 2016. “Dom w empirycznych sieciach leksykalnych”, *Etnolingwistyka. Problemy Języka i Kultury* 28: 117.

Gawarkiewicz, Roman, Izabela Pietrzyk and Barbara Rodziewicz. 2008. *Polski słownik asocjacyjny z suplementem*. Szczecin: Print Group.

Gerard, L. D. and D. L. Scarborough. 1989. “Language-specific lexical access of homographs by bilinguals”, *Journal of Experimental Psychology: Learning, Memory, and Cognition* 15, 2: 305-315.

Gilbert, Rebecca A., Matthew H. Davis, M. Gareth Gaskell and Jennifer M. Rodd. 2018. “Listeners and readers generalize their experience with word meanings across modalities”, *Journal of Experimental Psychology: Learning, Memory, and Cognition* 44, 10: 1533.

Glisky, Elizabeth L., Gene E. Alexander, Mingzhu Hou, Kevin Kawa, Cindy B. Woolverton, Erika K. Zigman, Lauren A. Nguyen, Kari Haws, Aurelio J. Figueredo and Lee Ryan. 2021. “Differences between young and older adults in unity and diversity of executive functions”, *Aging, Neuropsychology, and Cognition* 28, 6: 829-854.

Green, D. 1998. “Mental control of the bilingual lexico-semantic system” *Bilingualism: Language and Cognition* 1, 2: 67-81.

Griffiths, T., Steyvers, M. and J. Tenenbaum. 2007. “Topics in semantic representation”, *Psychological Review* 114, 2: 211-244.

de Groot, Annette M. B. 1995. “Determinants of bilingual lexicosemantic organisation”, *Computer Assisted Language Learning*, 8, 2-3: 151-180.

de Groot, Annette M. B. and G. L. Nas. 1991. “Lexical representation of cognates and noncognates in compound bilinguals”, *Journal of Memory and Language* 30, 1: 90-123.

de Groot, Annette M. B., Arnold J. W. M. Thomassen and Patrick T. W. Hudson. 1986. “Primed-lexical decision: The effect of varying the stimulus-onset asynchrony of prime and target”, *Acta Psychologica* 61, 1: 17-36.

Grosjean, François. 2021. *Life as a bilingual: Knowing and using two or more languages*. (1st edition.) Cambridge University Press.

Grundy, J. G. and K. Timmer. 2017. “Bilingualism and working memory capacity: A comprehensive meta-analysis”, *Second Language Research* 33, 3: 325-340.

Günther, Fritz, Luca Rinaldi and Marco Marelli. 2019. “Vector-space models of semantic representation from a cognitive perspective: A discussion of common misconceptions”, *Perspectives on Psychological Science* 14, 6: 1006-1033.

Harrison, Tyler L., Zach Shipstead and Randall W. Engle. 2015. “Why is working memory capacity related to matrix reasoning tasks?”, *Memory & Cognition* 43, 3: 389-396.

van Heuven, Walter J. B., Pawel Mandera, Emmanuel Keuleers and Marc Brysbaert. 2014. “Subtlex-UK: A new and improved word frequency database for British English”, *Quarterly Journal of Experimental Psychology* 67, 6: 1176-1190.

van Heuven, Walter J. B. 2020. *PseudoRandom List Generator (PRLG) (Version 2.30)* [Computer software]. (https://waltervanheuven.net/prlg/index.html) (date of access: 29 May 2023).

Heyman, Tom, Kirsten Goossens, Keith A. Hutchison and Gert Storms. 2017. “Does a working memory load *really* influence semantic priming? A self-replication attempt”, *Collabra: Psychology* 3, 1: 18.

Heyman, Tom, Bram Van Rensbergen, Gert Storms, Keith A. Hutchison and Simon De Deyne. 2015. “The influence of working memory load on semantic priming”, *Journal of Experimental Psychology: Learning, Memory, and Cognition* 41, 3: 911-920.

Hill, Holger, Marion Strube, Daniela Roesch-Ely and Matthias Weisbrod. 2002. “Automatic vs. controlled processes in semantic priming — differentiation by event-related potentials”, *International Journal of Psychophysiology* 44, 3: 197-218.

Horne, Autumn, Rachel Zahn, Oscar I. Najera and Randi C. Martin. 2022. “Semantic working memory predicts sentence comprehension performance: A case series approach”, *Frontiers in Psychology* 13: 887586.

Hutchison, Keith A. 2002. “The effect of asymmetrical association on positive and negative semantic priming”, *Memory & Cognition* 30, 8: 1263-1276.

Hutchison, Keith A. 2003. “Is semantic priming due to association strength or feature overlap? A microanalytic review”, *Psychonomic Bulletin & Review* 10, 4: 785-813.

Hutchison, Keith A., David A. Balota, Michael J. Cortese and Jason M. Watson. 2008. “Predicting semantic priming at the item level”, *Quarterly Journal of Experimental Psychology* 61, 7: 1036-1066.

Hutchison, Keith A., David A. Balota, James H. Neely, Michael J. Cortese, Emily R. Cohen-Shikora, Chi-Shing Tse, Melvin J. Yap, Jesse J. Bengson, Dale Niemeyer and Erin Buchanan. 2013. "The semantic priming project", *Behavior Research Methods* 45, 4: 1099-1114.

Hutchison, Keith A., Shelly J. Heap, James H. Neely and Matthew A. Thomas. 2014. "Attentional control and asymmetric associative priming", *Journal of Experimental Psychology: Learning, Memory, and Cognition* 40, 3: 844-856.

Jones, Michael N. and D. J. Mewhort. 2007. "Representing word meaning and order information in a composite holographic lexicon", *Psychological review* 114, 1: 1-37.

Jones, Michael N., Jon Willits and Simon Dennis. 2015. "Models of semantic memory", in: Jerome R. Busemeye, Zheng Wang, James T. Townsend and Ami Eidels (eds.), *The Oxford Handbook of Computational and Mathematical Psychology*. Oxford Library of Psychology, 232-254.

Kane, Michael J., Andrew R. A. Conway, Timothy K. Miura and Gregory J. H. Colflesh. 2007. "Working memory, attention control, and the n-back task: A question of construct validity", *Journal of Experimental Psychology: Learning, Memory, and Cognition* 33, 3: 615-622.

Kane, Michael J., David Z. Hambrick, Stephen W. Tuholski, Oliver Wilhelm, Tabitha W. Payne and Randall W. Engle. 2004. "The generality of working memory capacity: A latent-variable approach to verbal and visuospatial memory span and reasoning", *Journal of Experimental Psychology: General* 133, 2: 189-217.

Karr, Justin E., Corson N. Areshenkoff, Philippe Rast, Scott M. Hofer, Grant L. Iverson and Mauricio A. Garcia-Barrera. 2018. "The unity and diversity of executive functions: A systematic review and re-analysis of latent variable studies", *Psychological bulletin* 144, 11: 1147-1185.

Khanzhyn, Dmytro, Walter J. B. van Heuven and Karolina Rataj. In press. "The impact of spatial and verbal working memory load on semantic relatedness judgements", *Psychonomic Bulletin & Review*.

Keatley, Catharine W., John A. Spinks and Beatrice De Gelder. 1994. "Asymmetrical cross-language priming effects", *Memory & Cognition* 22, 1: 70-84.

Kent, Grace Helen and A. J. Rosanoff. 1910. "Part II. Association in insane subjects", in: *A study of association in insanity.* American Journal of Insanity, 16-72.

van Kesteren, Ron, Ton Dijkstra and Koenraad de Smedt. 2012. “Markedness effects in Norwegian-English bilinguals: Task-dependent use of language-specific letters and bigrams”, *Quarterly Journal of Experimental Psychology* 65, 11: 2129-2154.

Keuleers, E. and D. A. Balota. 2015. “Megastudies, crowdsourcing, and large datasets in psycholinguistics: An overview of recent developments”, *Quarterly Journal of Experimental Psychology*, 68, 8, 1457-1468.

Keuleers, E., M. Stevens, P. Mandera and M. Brysbaert. 2015. “Word knowledge in the crowd: Measuring vocabulary size and word prevalence in a massive online experiment”, *Quarterly Journal of Experimental Psychology*, 68, 8: 1665-1692.

Kiefer, Markus, Michelle Ahlegian and Manfred Spitzer. 2005. “Working memory capacity, indirect semantic priming, and Stroop interference: Pattern of interindividual prefrontal performance differences in healthy volunteers”, *Neuropsychology* 19, 3: 332-344.

Kim, S. 2022. “Working memory in word reading”, in: John W. Schwieter and Zhisheng (Edward) Wen (eds.), *The Cambridge Handbook of Working Memory and Language*. Cambridge: Cambridge University Press, 421-434.

Kim, So-Yeon, Min-Shik Kim and Marvin M. Chun. 2005. “Concurrent working memory load can reduce distraction”, *Proceedings of the National Academy of Sciences* 102, 45: 16524-16529.

Kiss, G., C. Armstrong, R. Milroy and J. Piper. 1973. “An associative thesaurus of English and its computer analysis”, in: A. J. Aitken, R. W. Bailey and N. Hamilton-Smith (eds.), *The computer and literary studies*. Edinburgh, UK: Edinburgh University Press, 153-165.

Kumar, Abhilasha A. 2021. “Semantic memory: A review of methods, models, and current challenges”, *Psychonomic Bulletin & Review* 28, 1: 40-80.

Kuperberg, Gina R., Balaji M. Lakshmanan, Douglas N. Greve and W. Caroline West. 2008. “Task and semantic relationship influence both the polarity and localization of hemodynamic modulation during lexico-semantic processing”, *Human Brain Mapping* 29, 5: 544-561.

Kurcz, Ida. 1967. “Polskie normy powszechności skojarzeń swobodnych na 100 słów z listy Kent-Rosanoffa”, *Studia Psychologiczne* 8: 122-255.

Kutas, Marta and Kara D. Federmeier. 2011. "Thirty years and counting: Finding meaning in the N400 component of the event-related brain potential (ERP)", *Annual Review of Psychology* 62: 621-647.

Kutas, Marta and Steven A. Hillyard. 1980. "Reading senseless sentences: Brain potentials reflect semantic incongruity", *Science* 207: 203-205.

Landauer, Thomas K. and Susan T. Dumais. 1997. "A solution to Plato's problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge", *Psychological Review* 104, 2: 211-240.

Landauer, Thomas K., Peter W. Foltz and Darrell Laham. 1998. "An introduction to latent semantic analysis", *Discourse Processes* 25, 2-3: 259-284.

Lazaridou, A., M. Marelli and M. Baroni. 2017. "Multimodal word meaning induction from minimal exposure to natural text", *Cognitive Science*, 41: 677-705.

Lehtonen, M., A. Soveri, A. Laine, J. Jarvenpaii, A. de Bruin and J. Antfolk. 2018. "Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review", *Psychological Bulletin* 144, 4: 394-425.

Lemhöfer, Kristin and Mirjam Broersma. 2012. "Introducing LexTALE: A quick and valid lexical test for advanced learners of English", *Behavior Research Methods* 44, 2: 325-343.

Lenci, Alessandro. 2018. "Distributional models of word meaning", *Annual Review of Linguistics* 4, 1: 151-171.

Lenth, Russell V. 2021. *emmeans: Estimated marginal means, aka least-squares means. R package version 1.7.0*. (https://CRAN.R-project.org/package=emmeans) (date of access: 29 May 2023).

Linck, J. A., P. Osthus, J. T. Koeth and M. F. Bunting. 2014. "Working memory and second language comprehension and production: A meta-analysis", *Psychonomic Bulletin & Review* 21, 4: 861-883.

Lo, Steson and Sally Andrews. 2015. "To transform or not to transform: Using generalized linear mixed models to analyse reaction time data", *Frontiers in Psychology* 6: 1171.

Logie, Robert H., Clément Belletier and Jason M. Doherty. 2020a. "Integrating theories of working memory", in: Robert Logie, Valerie Camos and Nelson Cowan (eds.), *Working Memory: State of the science*. Oxford: Oxford University Press, 389-429.

Logie, Robert H., Valérie Camos and Nelson Cowan (eds.). 2020b. *Working memory: State of the science*. Oxford: Oxford University Press.

Lu, Chen-hui and Robert W. Proctor. 1995. “The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects”, *Psychonomic Bulletin & Review* 2, 2: 174-207.

Lucas, Margery. 2000. “Semantic priming without association: A meta-analytic review”, *Psychonomic Bulletin & Review* 7, 4: 618-630.

Lüdecke, Daniel, Mattan S. Ben-Shachar, Indrajeet Patil, Philip Waggoner and Dominique Makowski. 2021. “Performance: An R package for assessment, comparison and testing of statistical models”, *Journal of Open Source Software* 6, 60: 3139.

Lund, Kevin and Curt Burgess. 1996. “Producing high-dimensional semantic spaces from lexical co-occurrence”, *Behavior Research Methods, Instruments, & Computers* 28, 2: 203-208.

Lupker, Stephen J., Giacomo Spinelli and Colin J. Davis. 2020. “Is zjudge a better prime for JUDGE than zudge is?: A new evaluation of current orthographic coding models”, *Journal of Experimental Psychology: Human Perception and Performance* 46, 11: 1252-1266.

Mandera, Paweł, Emmanuel Keuleers and Marc Brysbaert. 2015a. “How useful are corpus-based methods for extrapolating psycholinguistic variables?”, *Quarterly Journal of Experimental Psychology* 68, 8: 1623-1642.

Mandera, Paweł, Emmanuel Keuleers, Zofia Wodniecka and Marc Brysbaert. 2015b. “Subtlex-pl: subtitle-based word frequency estimates for Polish”, *Behavior Research Methods* 47, 2: 471-483.

Mandera, Paweł, Emmanuel Keuleers and Marc Brysbaert. 2017. “Explaining human performance in psycholinguistic tasks with models of semantic similarity based on prediction and counting: A review and empirical validation”, *Journal of Memory and Language* 92: 57-78.

Martin, Randi C. 2021. “The critical role of semantic working memory in language comprehension and production”, *Current Directions in Psychological Science* 30, 4: 283-291.

Martin, Randi C., Brenda Rapp and Jeremy Purcell. 2020. “Domain-specific working memory: Perspectives from cognitive neuropsychology”, in: Robert Logie, Valerie Camos and Nelson Cowan (eds.), *Working Memory: State of the science*. Oxford: Oxford University Press, 235-281.

Martin, Randi C. and Tao He. 2004. “Semantic short-term memory and its role in sentence processing: A replication”, *Brain and Language* 89, 1: 76-82.

Mashburn, Cody A., Jason S. Tsukahara and Randall W. Engle. 2020. “Individual differences in attention control: Implications for the relationship between working memory capacity and fluid intelligence”, in: Robert Logie, Valerie Camos and Nelson Cowan (eds.), *Working Memory: State of the science*. Oxford: Oxford University Press, 175-211.

Masson, Michael E. J. 1995. “A distributed memory model of semantic priming”, *Journal of Experimental Psychology: Learning, Memory, and Cognition* 21: 3-23.

McClelland, James L. and David E. Rumelhart. 1985. “Distributed memory and the representation of general and specific information”, *Journal of Experimental Psychology: General* 114, 2: 159-188.

McKoon, G. and R. Ratcliff. 1992. “Spreading activation versus compound cue accounts of priming: mediated priming revisited”, *Journal of Experimental Psychology. Learning, Memory, and Cognition* 18, 6: 1155-1172.

McNamara, Timothy P. 2005. *Semantic priming: Perspectives from memory and word recognition*. New York: Psychology Press.

McNamara, Timothy P and Jeanette Altarriba. 1988. “Depth of spreading activation revisited: Semantic mediated priming occurs in lexical decisions”, *Journal of Memory and Language* 27, 5: 545-559.

McRae, Ken. 2004. “Semantic memory: Some insights from feature-based connectionist attractor networks”, *Psychology of Learning and Motivation* 45: 41-86.

McRae, Ken, George S. Cree, Mark S. Seidenberg and Chris McNorgan. 2005. “Semantic feature production norms for a large set of living and nonliving things”, *Behavior Research Methods* 37, 4: 547-559.

McRae, Ken, Saman Khalkhali and Mary Hare. 2012. “Semantic and associative relations in adolescents and young adults: Examining a tenuous dichotomy”, in: Valerie F. Reyna, Sandra B. Chapman, Michael R. Dougherty and Jere Confrey (eds.), *The adolescent brain: Learning, reasoning, and decision making.* Washington: American Psychological Association, 39-66.

McRae, Ken, Virginia R. de Sa and Mark S. Seidenberg. 1997. “On the nature and scope of featural representations of word meaning”, *Journal of Experimental Psychology. General* 126, 2: 99-130.

Meteyard, Lotte, Sara Rodriguez Cuadrado, Bahador Bahrami and Gabriella Vigliocco. 2012. “Coming of age: A review of embodiment and the neuroscience of semantics”, *Cortex* 48, 7: 788-804.

Meteyard, Lotte and Gabriella Vigliocco. 2018. “Lexico-Semantics”, in: Shirley-Ann Rueschemeyer and M. Gareth Gaskell (eds.), *The Oxford Handbook of Psycholinguistics*. Oxford University Press, 70-95.

Meyer, David E. and Roger W. Schvaneveldt. 1971. “Facilitation in recognizing pairs of words: Evidence of a dependence between retrieval operations”, *Journal of Experimental Psychology* 90, 2: 227-234.

Mikolov, Tomas, Kai Chen, Greg Corrado and Jeffrey Dean. 2013. “Efficient estimation of word representations in vector space” (http://arxiv.org/abs/1301.3781) (date of access: 5 Feb. 2023).

Mikolov, Tomas, Edouard Grave, Piotr Bojanowski, Christian Puhrsch and Armand Joulin. 2017. “Advances in pre-training distributed word representations” (http://arxiv.org/abs/1712.09405) (date of access: 23 Mar. 2023).

Miller, George A. 1992. “WordNet: A lexical database for English”, in: *Speech and Natural Language: Proceedings of a Workshop Held at Harriman, New York, February 23-26, 1992*.

Miller, George A. 1995. “WordNet: A lexical database for English”, *Communications of the ACM* 38, 11: 39-41.

Mitchell, Jason P., C. Neil Macrae and Iain D. Gilchrist. 2002. “Working memory and the suppression of reflexive saccades”, *Journal of Cognitive Neuroscience* 14, 1: 95-103.

Miyake, Akira and Naomi P. Friedman. 2012. “The nature and organization of individual differences in executive functions: Four general conclusions”, *Current Directions in Psychological Science* 21, 1: 8-14.

Miyake, Akira, Naomi P. Friedman, Michael J. Emerson, Alexander H. Witzki, Amy Howerter and Tor D. Wager. 2000. “The unity and diversity of executive functions and their contributions to complex ‘frontal lobe’ tasks: A latent variable analysis”, *Cognitive Psychology* 41, 1: 49-100.

Morford, Jill P., Erin Wilkinson, Agnes Villwock, Pilar Piñar and Judith F. Kroll. 2011. "When deaf signers read English: Do written words activate their sign translations?", *Cognition* 118, 2: 286-292.

Moss, H. E., M. L. Hare, P. Day and L. K. Tyler. 1994. "A distributed memory model of the associative boost in semantic priming" *Connection Science* 6, 413-427.

Mykowiecka, Agnieszka, Małgorzata Marciniak and Piotr Rychlik. 2017. "Testing word embeddings for Polish", *Cognitive Studies* 17.

Nagel, Bonnie J., Megan M. Herting, Emily C. Maxwell, Richard Bruno and Damien Fair. 2013. "Hemispheric lateralization of verbal and spatial working memory during adolescence", *Brain and Cognition* 82, 1: 58-68.

Nagel, Bonnie J., Arthur Ohannessian and Kevin Cummins. 2007. "Performance dissociation during verbal and spatial working memory tasks", *Perceptual and Motor Skills* 105, 1: 243-250.

Neely, James H. 1976. "Semantic priming and retrieval from lexical memory: Evidence for facilitatory and inhibitory processes", *Memory & Cognition* 4, 5: 648-654.

Neely, James H. 1991. "Semantic priming effects in visual word recognition: A selective review of current findings and theories", in: D. Besner and G. W. Humphreys (eds.), *Basic processes in reading: Visual word recognition*. Lawrence Erlbaum Associates, Inc., 264-336.

Neely, James H. and D. E. Keefe. 1989. "Semantic context effects on visual word processing: A hybrid prospective/retrospective processing theory", in: G. H. Bower (ed.), *The psychology of learning and motivation, Vol. 24*. New York, NY: Academic Press, 207-248.

Neely, James H. and Todd A. Kahan. 2001. "Is semantic activation automatic? A critical re-evaluation", in: Henry L. Roediger, James S. Nairne, Ian Neath and Aimée M. Surprenant (eds.), *The nature of remembering: Essays in honor of Robert G. Crowder.* Washington: American Psychological Association, 69-93.

Nelson, Douglas L., Cathy L. McEvoy and Thomas A. Schreiber. 1998. *The University of South Florida word association, rhyme, and word fragment norms*. (http://w3.usf.edu/FreeAssociation/) (date of access: 25 Mar. 2023).

Nelson, Douglas L., Cathy L. McEvoy and Thomas A. Schreiber. 2004. "The University of South Florida free association, rhyme, and word fragment norms", *Behavior Research Methods, Instruments, & Computers* 36, 3: 402-407.

Newman, Aaron J., Antoine Tremblay, Emily S. Nichols, Helen J. Neville and Michael T. Ullman. 2012. “The influence of language proficiency on lexical semantic processing in native and late learners of English”, *Journal of Cognitive Neuroscience* 24, 5: 1205-1223.

Ning, Siqi, Sayuri Hayakawa, James Bartolotti and Viorica Marian. 2020. “On language and thought: Bilingual experience influences semantic associations”, *Journal of Neurolinguistics* 56: 100932.

van den Noort, Maurits, Peggy Bosch, Marco Haverkort and Kenneth Hugdahl. 2008. “A standard computerized version of the reading span test in different languages”, *European Journal of Psychological Assessment* 24, 1: 35-42.

Ober, Teresa M., Patricia J. Brooks, Bruce D. Homer and David Rindskopf. 2020. “Executive functions and decoding in children and adolescents: A meta-analytic investigation”, *Educational Psychology Review* 32, 3: 735-763.

Oberauer, Klaus. 2020. “Towards a theory of working memory: From metaphors to mechanisms”, in: Robert Logie, Valerie Camos and Nelson Cowan (eds.), *Working Memory: State of the science*. Oxford: Oxford University Press, 116-149.

Ortells, Juan J., Dolores Álvarez, Carmen Noguera, Encarna Carmona and Jan W. de Fockert. 2017. “The influence of working memory load on expectancy-based strategic processes in the Stroop-priming task”, *Frontiers in Psychology* 8: 129.

Ortells, Juan J., Jan W. De Fockert, Nazaret Romera and Sergio Fernández. 2018. “Expectancy-based strategic processes are influenced by spatial working memory load and individual differences in working memory capacity”, *Frontiers in Psychology* 9: 1239.

Ortells, Juan J., Carmen Noguera, Dolores Álvarez, Encarna Carmona and George Houghton. 2016. “Individual differences in working memory capacity modulates semantic negative priming from single prime words”, *Frontiers in Psychology* 7: 1286.

Ortu, Daniele, Kevin Allan and David I. Donaldson. 2013. “Is the N400 effect a neurophysiological index of associative relationships?”, *Neuropsychologia* 51, 9: 1742-1748.

Paap, Kenneth R. and Ronald W. Noel. 1991. “Dual-route models of print to sound: Still a good horse race”, *Psychological Research* 53, 1: 13-24.

Page, Mike. 2000. “Connectionist modelling in psychology: A localist manifesto” *Behavioral and Brain Sciences* 23, 4: 443-467.

Peirce, Jonathan, Jeremy R. Gray, Sol Simpson, Michael MacAskill, Richard Höchenberger, Hiroyuki Sogo, Erik Kastman and Jonas Kristoffer Lindeløv. 2019. "PsychoPy2: Experiments in behavior made easy", *Behavior Research Methods* 51, 1: 195-203.

Perea, Manuel, Jon Andoni Duñabeitia and Manuel Carreiras. 2008. "Masked associative/semantic priming effects across languages with highly proficient bilinguals", *Journal of Memory and Language* 58, 4: 916-930.

Perea, Manuel, Ana Marcet, Mario Lozano and Pablo Gomez. 2018. "Is masked priming modulated by memory load? A test of the automaticity of masked identity priming in lexical decision", *Memory & Cognition* 46, 7: 1127-1135.

Perea, Manuel and Eva Rosa. 2002. "The effects of associative and semantic priming in the lexical decision task", *Psychological Research* 66, 3: 180-194.

Phillips, Natalie A., Norman Segalowitz, Irena O'Brien and Naomi Yamasaki. 2004. "Semantic priming in a first and second language: Evidence from reaction time variability and event-related brain potentials", *Journal of Neurolinguistics* 17, 2-3: 237-262.

Pierce, Lara J., Fred Genesee, Audrey Delcenserie and Gary Morgan. 2017. "Variations in phonological working memory: Linking early language experiences and language learning outcomes", *Applied Psycholinguistics* 38, 6: 1265-1300.

Plaut, David C. 1995. "Double dissociation without modularity: Evidence from connectionist neuropsychology", *Journal of Clinical and Experimental Neuropsychology* 17, 2: 291-321.

Plaut, David C. and James R. Booth. 2000. "Individual and developmental differences in semantic priming: Empirical and computational support for a single-mechanism account of lexical processing", *Psychological Review* 107, 4: 786-823.

Poole, Bradley J. and Michael J. Kane. 2009. "Working-memory capacity predicts the executive control of visual search among distractors: The influences of sustained and selective attention", *Quarterly Journal of Experimental Psychology* 62, 7: 1430-1454.

Poort, Eva D. and Jennifer M. Rodd. 2019. "Towards a distributed connectionist account of cognates and interlingual homographs: Evidence from semantic relatedness tasks", *PeerJ* 7: e6725.

Poort, Eva D. and Jennifer M. Rodd. 2022. "Cross-lingual priming of cognates and interlingual homographs from L2 to L1", *Glossa Psycholinguistics* 1, 1: 1-33.

Posner, M. I. and C. R. R. Snyder. 1975. “Attention and cognitive control”, in: R. L. Solso (ed.), *Information processing and cognition: The Loyola symposium*. Hillsdale, NJ: Erlbaum, 55-85.

Postle, Bradley R. 2020. “Cognitive neuroscience of visual working memory”, in: Robert Logie, Valerie Camos and Nelson Cowan (eds.), *Working Memory: State of the science*. Oxford: Oxford University Press, 333-357.

Pratte, Michael S., Jeffrey N. Rouder, Richard D. Morey and Chuning Feng. 2010. “Exploring the differences in distributional properties between Stroop and Simon effects using delta plots”, *Attention, Perception, & Psychophysics* 72, 7: 2013-2025.

Przepiórkowski, Adam, Mirosław Bańko, Rafał L. Górski and Barbara Lewandowska-Tomaszczyk (eds.). 2012. *Narodowy korpus języka polskiego: Praca zbiorowa*. Warszawa: Wydawnictwo Naukowe PWN.

R Core Team. 2021. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. (http://www.R-project.org/) (date of access: 29 May 2023).

Radel, Rémi, Karen Davranche, Marion Fournier and Arne Dietrich. 2015. “The role of (dis)inhibition in creativity: Decreased inhibition improves idea generation”, *Cognition* 134: 110-120.

Rataj, Karolina, Patrycja Kakuba, Paweł Mandera and Walter J. B. van Heuven. 2023. “Establishing semantic relatedness through ratings, reaction times, and semantic vectors: A database in Polish”, *PLOS ONE* 18, 4: e0284801.

Rataj, Karolina and Walter J. B. van Heuven. In preparation. Impact of a non-linguistic executive control task on a subsequent semantic relatedness task: An ERP study (working title).

Ratcliff, R. and G. McKoon. 1995. “Sequential effects in lexical decision: Tests of compound-cue retrieval theory”, *Journal of experimental psychology. Learning, memory, and cognition* 21, 5: 1380-1388.

Ridderinkhof, K. Richard, Wery P. M. van den Wildenberg, Jasper Wijnen and Borís Burle. 2004. “Response inhibition in conflict tasks is revealed in delta plots”, in: M. I. Posner (ed.), *Cognitive neuroscience of attention*. New York, NY, US: The Guilford Press, 369-377.

Riffle, Travis L. and Jeffrey J. DiGiovanni. 2017. “Accounting for verbal and spatial working memory load in an auditory Stroop task”, *Proceedings of Meetings on Acoustics* 30: 050014.

Roelofs Ardi, Vitória Piai and Gabriela Garrido Rodriguez. 2011. “Attentional inhibition in bilingual naming performance: Evidence from delta-plot analyses”, *Frontiers in Psychology* 2: 184.

Sauter, Marian, Dejan Draschkow and Wolfgang Mack. 2020. “Building, hosting and recruiting: A brief introduction to running behavioral experiments online”, *Brain Sciences* 10, 4: 251.

Schoonbaert, Sofie, Wouter Duyck, Marc Brysbaert and Robert J. Hartsuiker. 2009. “Semantic and translation priming from a first language to a second and back: Making sense of the findings”, *Memory & Cognition* 37, 5: 569-586.

Schwarz, Wolf and Jeff Miller. 2012. “Response time models of delta plots with negative-going slopes”, *Psychonomic Bulletin & Review* 19, 4: 555-574.

Schwieter, John W. and Zhisheng (Edward) Wen (eds.). 2022a. *The Cambridge Handbook of Working Memory and Language*. Cambridge: Cambridge University Press.

Schwieter, John W. and Zhisheng (Edward) Wen. 2022b. “Working memory and language: An overview of key topics”, in: John W. Schwieter and Zhisheng (Edward) Wen (eds.), *The Cambridge Handbook of Working Memory and Language*. Cambridge University Press, 3-16.

Shah, Priti and Akira Miyake. 1996. “The separability of working memory resources for spatial thinking and language processing: An individual differences approach”, *Journal of Experimental Psychology: General* 125, 1: 4-27.

Shipstead, Zach, Tyler L. Harrison and Randall W. Engle. 2012. “Working memory capacity and visual attention: Top-down and bottom-up guidance”, *Quarterly Journal of Experimental Psychology* 65, 3: 401-407.

Simon, J. Richard and A. M. Small. 1969. “Processing auditory information: Interference from an irrelevant cue”, *Journal of Applied Psychology* 53, 5: 433-435.

Singmann, Henrik, Ben Bolker, Jake Westfall, Frederik Aust and Mattan S. Ben-Shachar. 2021. *afex: Analysis of factorial experiments. R package version 1.0-1*. (http://CRAN.Rproject.org/package=afex) (date of access: 29 May 2023).

Smith, Edward E., John Jonides and Robert A. Koeppe. 1996. “Dissociating verbal and spatial working memory using PET”, *Cerebral Cortex* 6, 1: 11-20.

Smith, Edward E., Edward J. Shoben and Lance J. Rips. 1974. “Structure and process in semantic memory: A featural model for semantic decisions”, *Psychological Review* 81, 3: 214-241.

Smith, Yisrael, Joel Walters and Anat Prior. 2019. “Target accessibility contributes to asymmetric priming in translation and cross-language semantic priming in unbalanced bilinguals”, *Bilingualism: Language and Cognition* 22, 1: 157-176.

Steyvers, Mark and Joshua B. Tenenbaum. 2005. “The large-scale structure of semantic networks: Statistical analyses and a model of semantic growth”, *Cognitive Science* 29, 1: 41-78.

Stroop, J. R. 1935. “Studies of interference in serial verbal reactions”, *Journal of Experimental Psychology* 18, 6: 643-662.

Swanson, H. Lee. 2017. “Verbal and visual-spatial working memory: What develops over a life span?”, *Developmental Psychology* 53, 5: 971-995.

Szmalec, Arnaud, Marc Brysbaert and Wouter Duyck. 2012. “Working memory and (second) language processing”, in: Jeanette Altarriba and Ludmila Isurin (eds.), *Memory, Language, and Bilingualism: Theoretical and Applied Approaches*. Cambridge: Cambridge University Press, 74-94.

Telesford, Qawi K., Karen E. Joyce, Satoru Hayasaka, Jonathan H. Burdette and Paul J. Laurienti. 2011. “The ubiquity of small-world networks”, *Brain connectivity* 1, 5: 367-375.

Thierry, Guillaume and Yan Jing Wu. 2007. “Brain potentials reveal unconscious translation during foreign-language comprehension”, *Proceedings of the National Academy of Sciences* 104, 30: 12530-12535.

Thomas, Matthew A., James H. Neely and Patrick O’Connor. 2012. “When word identification gets tough, retrospective semantic processing comes to the rescue”, *Journal of Memory and Language* 66, 4: 623-643.

Thompson-Schill, Sharon L., Kenneth J. Kurtz and John D.E. Gabrieli. 1998. “Effects of semantic and associative relatedness on automatic priming”, *Journal of Memory and Language* 38, 4: 440-458.

Turney, Peter D. 2006. “Similarity of semantic relations”, *Computational Linguistics* 32, 3: 379-416.

Tversky, Amos. 1977. “Features of similarity”, *Psychological Review* 84, 4: 327-352.

Tytus, Agnieszka Ewa and Gabriella Rundblad. 2016. “Cross-language priming as a means of investigating bilingual conceptual representations: A comparison of visual and auditory modality”, *Linguistic Approaches to Bilingualism* 6, 4: 440-466.

Unsworth, Nash, Thomas S. Redick, Richard P. Heitz, James M. Broadway and Randall W. Engle. 2009. “Complex working memory span tasks and higher-order cognition: A latent-variable analysis of the relationship between processing and storage”, *Memory* 17, 6: 635-654.

Vandierendonck, André. 2020. “Multicomponent working memory system with distributed executive control”, in: Robert Logie, Valerie Camos and Nelson Cowan (eds.), *Working Memory: State of the science*. Oxford: Oxford University Press, 150-174.

Vigliocco, Gabriella and David P. Vinson. 2012. “Semantic representation”, in: M. Gareth Gaskell (ed.), *The Oxford Handbook of Psycholinguistics*. Oxford University Press, 195-216.

Vigliocco, Gabriella, Lotte Meteyard, Mark Andrews and Stavroula Kousta. 2009. “Toward a theory of semantic representation”, *Language and Cognition* 1, 2: 219-247.

Vigliocco, Gabriella, David P. Vinson, William Lewis and Merrill F Garrett. 2004. “Representing the meanings of object and action words: The featural and unitary semantic space hypothesis”, *Cognitive Psychology* 48, 4: 422-488.

Vivas, Leticia, Laura Manoiloff, Adolfo M. García, Francisco Lizarralde and Jorge Vivas. 2019. “Core semantic links or lexical associations: Assessing the nature of responses in word association tasks”, *Journal of Psycholinguistic Research* 48, 1: 243-256.

Watts, Duncan J and Steven H Strogatz. 1998. “Collective dynamics of ‘small-world’ networks”, *Nature*, 393: 440-442.

Waters, Gloria S. and David Caplan. 1996. “The measurement of verbal working memory capacity and its relation to reading comprehension”, *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology*, 49A, 1: 51-79.

Wen, Zhisheng (Edward). 2016. *Working memory and second language learning: Towards an integrated approach*. Bristol: Multilingual Matters.

Wen, Yun and Walter J. B. van Heuven. 2017. “Non-cognate translation priming in masked priming lexical decision experiments: A meta-analysis”, *Psychonomic Bulletin & Review* 24, 3: 879-886.

Wen, Yun and Walter J. B. van Heuven. 2018. “Limitations of translation activation in masked priming: Behavioural evidence from Chinese-English bilinguals and computational modelling”, *Journal of Memory and Language* 101: 84-96.

Wen, Zhisheng (Edward). 2019. “Working memory as language aptitude: The phonological/executive model”, in: Zhisheng (Edward) Wen, Peter Skehan, Adriana Biedroń, Shaofeng Li and Richard L. Sparks (eds.), *Language Aptitude: Advancing Theory, Testing, Research and Practice (1st ed.).* Routledge, 277-338.

Wu, Yan Jing and Guillaume Thierry. 2010. “Chinese–English bilinguals reading English hear Chinese”, *The Journal of Neuroscience* 30, 22: 7646-7651.

Xavier Alario, F., Juan Segui and Ludovic Ferrand. 2000. “Semantic and associative priming in picture naming”, *The Quarterly Journal of Experimental Psychology Section A* 53, 3: 741-764.

Zahn, Rachel, Autumn Horne and Randi C. Martin. 2022. “The role of working memory in language comprehension and production: Evidence from neuropsychology”, in: John W. Schwieter and Zhisheng (Edward) Wen (eds.), *The Cambridge Handbook of Working Memory and Language*. Cambridge: Cambridge University Press, 435-458.

Zhang, Taoli, Walter J. B. van Heuven and Kathy Conklin. 2011. “Fast automatic translation and morphological decomposition in Chinese-English bilinguals”, *Psychological Science* 22, 10: 1237-1242.

Zhao, Xiao, Antao Chen and Robert West. 2010. “The influence of working memory load on the Simon effect”, *Psychonomic Bulletin & Review* 17, 5: 687-692.

Appendix A: Cue words, for which at least one association response matched semantically related target words from Rataj et al. (2023), and match rates for all responses combined and for first (R1), second (R2) and third (R3) responses

Cue word	Response / Target word	Overall match rate	R1 match rate	R2 match rate	R3 match rate
oprawki (glasses frame)	okulary (glasses)	1	0.96	0	0.04
odrzutowiec (jet)	samolot (plane)	0.79	0.67	0.08	0.04
niedopałek (cigarette end)	papieros (cigarette)	0.7	0.48	0.15	0.04
wybrzeże (coast)	morze (sea)	0.65	0.58	0.08	0
szkic (sketch)	rysunek (painting)	0.65	0.58	0.08	0
skoroszyt (workbook)	zeszyt (notebook)	0.58	0.54	0.04	0
przyśpiewka (refrain)	piosenka (song)	0.48	0.36	0.12	0
szrama (scar)	blizna (scar)	0.48	0.22	0.17	0.09
grzywka (fringe)	fryzura (haircut)	0.48	0.15	0.2	0.12
podesty (platform)	schody (steps)	0.44	0.36	0.04	0.04
płaszczka (stingray)	ryba (fish)	0.4	0.28	0.04	0.08
prostokąt (rectangle)	kwadrat (square)	0.37	0.26	0.07	0.04
kij (stick)	patyk (stick)	0.37	0.22	0.15	0
rozlewisko (flood waters)	jezioro (lake)	0.35	0.04	0.22	0.09
surdut (frock coat)	garnitur (suit)	0.31	0.19	0.04	0.08

akwen (basin)	basen (swimming pool)	0.27	0.15	0.12	0
kran (tap)	zlew (sink)	0.27	0.04	0.12	0.12
powłoka (coating)	warstwa (layer)	0.26	0.15	0	0.11
podatnik (taxpayer)	obywatel (citizen)	0.22	0.11	0.07	0.04
dolina (valley)	rzeka (river)	0.2	0.04	0.08	0.08
tułów (torso)	brzuch (stomach)	0.19	0.04	0.07	0.07
bydło (cattle)	stado (herd)	0.15	0	0	0.15
talerzyk (small plate)	widelec (fork)	0.15	0.04	0.07	0.04
szałas (shelter)	namiot (tent)	0.12	0.08	0	0.04
ulewa (downpour)	burza (storm)	0.12	0	0.08	0.04
przytulanka (soft toy)	zabawka (toy)	0.11	0	0.11	0
gmach (building)*	zamek (castle)	0.08	0.04	0	0.04
pisklę (chick)	jajo (egg)	0.08	0.04	0	0.04
spiżarnia (larder)	kuchnia (kitchen)	0.08	0	0.04	0.04
wójt (borough leader)	burmistrz (mayor)	0.08	0.04	0.04	0
łydki (calves)*	spodnie (trousers)	0.07	0	0.04	0.04
grzbiet (back)	garb (hump)	0.07	0	0.04	0.04
kamienica (tenement)	ulica (street)	0.07	0	0.04	0.04
batonik (chocolate bar)	cukierek (candy)	0.04	0	0	0.04
powieki (eyelids)*	okulary (glasses)	0.04	0	0.04	0
żaglówka (sailing boat)*	zatoka (bay)	0.04	0	0	0.04
wise (village)*	rzeka (river)	0.04	0	0	0.04
dwór (estate/court)	zamek (castle)	0.04	0	0	0.04
kawa (coffee)	herbata (tea)	0.04	0	0	0.04
kołnierzyk (small collar)	krawat (tie)	0.04	0.04	0	0
legowisko (den)	gniazdo (nest)	0.04	0	0.04	0
majątek (wealth)	skarb (treasure)	0.04	0.04	0	0
młodzieniec (young man)	staruszek (old man)	0.04	0	0	0.04
nadajnik (transmitter)	odbiornik (receiver)	0.04	0	0.04	0
nadzienie (filling)	ciasto (cake)	0.04	0.04	0	0

krwiak (haematoma)	skrzep (clot)	0.04	0.04	0	0
ramiona (shoulders)	plecy (back)	0.04	0	0.04	0
rzeźbiarz (sculptor)	malarz (painter)	0.04	0.04	0	0
sztolnia (adit)	jaskinia (cave)	0.04	0.04	0	0
pieróg (dumpling)*	garnek (pot)	0.04	0	0.04	0
włócznia (spear)	tarcza (shield)	0.04	0	0	0.04
wyszukiwarka (browser)	strona (page)	0.04	0	0	0.04
zagroda (homestead)	chata (cottage)	0.04	0.04	0	0
zawał (heart attack)	udar (stroke)	0.04	0.04	0	0

Note. Weakly related primes are marked with *

Appendix B: Critical word pairs in Study 3

Related word	Unrelated word	Target
Backward associates (BA)		
wrong	weight	CORRECT
tired	together	SLEEPY
cow	dead	HERD
together	end	UNITE
end	dog	CONCLUDE
dead	money	CORPSE
joke	tree	PUN
cut	bird	TRIM
bird	small	HAWK
fire	tired	BLAZE
money	fire	TAX
tree	joke	MOSS
small	cow	SHRINK
weight	cut	SCALES
dog	wrong	BREED
door	mad	KNOCK
head	door	SKULL
mad	short	ANGER
take	sleep	REMOVE
think	run	CONSIDER
run	need	FLEE
loud	head	NOISY
fast	ask	RAPID
kiss	take	LIPS
sleep	think	NAP
short	fast	BRIEF

done	kiss	FINISHED
ask	open	REQUEST
need	done	NECESSARY
open	loud	CLOSED
Forward associates (FA)		
famine	peel	HUNGER
elk	tote	DEER
truthful	quill	HONEST
quill	tickle	PEN
cobweb	mare	SPIDER
mare	trousers	HORSE
silence	butcher	QUIET
elbow	silence	ARM
shears	elbow	SCISSORS
tickle	elk	LAUGH
butcher	shears	MEAT
trousers	dagger	PANTS
dagger	cobweb	KNIFE
tote	truthful	BAG
peel	famine	ORANGE
crescent	powerful	MOON
spool	dine	THREAD
lollipop	syringe	CANDY
touchdown	sentry	FOOTBALL
syringe	nauseous	NEEDLE
lumber	fracture	WOOD
fracture	spool	BREAK
powerful	touchdown	STRONG
shutter	hornet	WINDOW
dim	lollipop	LIGHT
nauseous	shutter	SICK
hornet	crescent	BEE
dine	dim	EAT
sentry	annual	GUARD
annual	lumber	YEARLY
Symmetric associates (SYM)		
outside	innocent	INSIDE
son	stupid	DAUGHTER
innocent	dryer	GUILTY
stupid	uncle	DUMB
dryer	fork	WASHER
scream	full	YELL
wife	scream	HUSBAND

hammer	gold	NAIL
borrow	wife	LEND
male	borrow	FEMALE
loose	male	TIGHT
gold	loose	SILVER
uncle	outside	AUNT
full	son	EMPTY
fork	hammer	SPOON
garbage	north	TRASH
monkey	salt	APE
west	monkey	EAST
verb	poor	NOUN
salt	verb	PEPPER
push	man	SHOVE
man	dime	WOMAN
black	garbage	WHITE
remember	black	FORGET
today	forward	TOMORROW
poor	west	RICH
north	push	SOUTH
dime	increase	NICKEL
forward	remember	BACKWARD
increase	today	DECREASE