Zooming in on speech production:
Cumulative semantic interference and the processing of compounds

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Anna-Lisa Döring, M.A

Präsidentin der Humboldt-Universität zu Berlin
Prof. Dr. Julia von Blumenthal

Dekan der Lebenswissenschaftlichen Fakultät der Humboldt-Universität zu Berlin
Prof. Dr. Dr. Christian Ulrichs

Gutachter:innen:
1. Dr. Antje Lorenz
2. Prof. Dr. Eva Belke
3. Dr. Fritz Günther

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Abstract

We easily produce thousands of words a day, if our cognitive and physical abilities allow us to. Yet much remains to be learned about the underlying processes of speech production. In this dissertation, I address unresolved issues concerning speech production processes and the cognitive architecture of our speech production system. My aim was two-fold: The first aim was to answer the question how compounds (e.g., *goldfish*) are represented on the lexical-syntactic level of our speech production system. Is there a single entry for the whole compound (*GOLDFISH*) or multiple ones for each of its constituents (*GOLD* and *FISH*), which are assembled for each use? Understanding how these morphologically complex words are represented in our mental lexicon adds an additional piece to the puzzle that is the structure of the speech production system. To investigate this question, I used the cumulative semantic interference (CSI) effect. This semantic context effect describes the observation that speakers' naming latencies systematically increase when naming a sequence of semantically related pictures. Although CSI has been extensively used as a tool in language production research, several aspects of it are not fully understood. Thus, the second aim of this dissertation was to close some of these knowledge gaps and gain a more comprehensive understanding of CSI. In three studies, I first investigated cumulative interference behaviourally (Study 1) and electrophysiologically (Study 2) and then used the effect to investigate the lexical representation of compounds (Study 3).

The results of the behavioural and electrophysiological data in Study 1 and 2 point to a purely conceptual origin of CSI. Furthermore, the studies revealed that CSI is not influenced by the items' morphological complexity but affected by item repetition. These findings advance our understanding of CSI and thus allow me and future researchers to make more informed predictions when using CSI as a research tool. In Study 3, CSI showed that the compounds' constituents are activated during compound production, which provides evidence for a complex lexical-syntactic representation of compounds, consisting of one entry for the holistic compound and additional entries for each of its constituents. This dissertation thus reveals that the morphological complexity of compounds affects the lexical-syntactic level during speech production and thus advances our understanding of the architecture of our speech production system.

Zusammenfassung

Wir produzieren mühelos tausende Wörter pro Tag und trotzdem gibt es noch viel über die zugrundeliegenden Prozesse der Wortproduktion zu lernen. Diese Dissertation beschäftigt sich mit einigen ungeklärten Aspekten der Sprachproduktion und verfolgte dabei zwei Ziele: Das erste Ziel war es die Frage zu beantworten, wie Komposita (z.B. *Goldfisch*) auf der lexikalisch-syntaktischen Ebene unseres Sprachproduktionssystems repräsentiert sind (Studie 3). Gibt es dort einen einzelnen lexikalischen Eintrag für das gesamte Kompositum (*GOLDFISCH*) oder mehrere Einträge für jedes seiner Konstituenten (*GOLD* und *FISCH*), welche beim Sprechen zusammengesetzt werden? Das Wissen darüber, wie diese morphologisch komplexen Wörter in unserem mentalen Lexikon repräsentiert sind, bringt uns einen Schritt näher das komplexe Sprachproduktionssystem in seiner Gänze zu verstehen. Um diese Frage zu beantworten, verwendete ich die sogenannte kumulative semantische Interferenz (KSI). Dieser semantische Kontexteffekt beschreibt die Beobachtung, dass die Benennlatenzen von Sprechern systematisch länger werden, wenn diese eine Reihe von semantisch verwandten Bildern benennen. Obwohl KSI bereits viel als Instrument in der Sprachproduktionsforschung genutzt wird, sind einige Fragen rund um den Effekt selbst noch offen. Das zweite Ziel dieser Dissertation war es daher einige dieser Fragen mit Hilfe von behavioralen und elektrophysiologischen Maßen zu beantworten (Studie 1 und 2), um so unser Verständnis von KSI zu erweitern.

Die Ergebnisse aus Studie 1 und 2 deuten darauf hin, dass KSI ihren Ursprung auf der konzeptuellen Ebene des Sprachproduktionssystems hat und dass sie nicht von der morphologischen Komplexität der verwendeten Begriffe moduliert wird, aber davon, wie häufig diese benannt werden. Diese Erkenntnisse erweitern unser Verständnis von KSI und ermöglichen es in der Zukunft zielgenauere Vorhersagen zu machen, wenn KSI als Forschungsinstrument verwendet wird. In Studie 3 hat KSI gezeigt, dass die Konstituenten von Komposita während deren Produktion aktiviert werden. Dies belegt, dass Komposita in einer komplexen Struktur repräsentiert sind, die aus einem Eintrag für das ganze Kompositum und zusätzlichen Einträgen für die Konstituenten besteht. Somit zeigen diese Ergebnisse, dass die Morphologie bereits die Repräsentationen auf der lexikalisch-syntaktischen Ebene beeinflusst und erweitern somit unser Wissen über den Aufbau unseres Sprachproduktionssystems.

Synopsis

1. Introduction

Speaking enables us to share facts, ideas and emotions with others and we easily produce thousands of words a day. The seemingly simple and effortless act of producing a word, however, is in fact a concatenation and interaction of various complex processes: After activating the conceptual information of our intended message, the corresponding lexical entries for this concept need to be selected from our mental lexicon, before we can finally initiate phonetic encoding and the articulation process (Dell, 1986; Levelt et al., 1999). For monomorphemic words, such as *tooth* or *fish*, lexical-semantic encoding seems rather straight forward: simply select the lexical entry (*fish*) that best expresses your intended message (FISH). However, things are more complicated for morphologically complex words, such as *toothbrush* or *goldfish*. As these noun-noun compounds are built from multiple existing words (*gold* and *fish* for *goldfish*), it is still under debate how they are lexically represented in our mental lexicon (e.g., Levelt et al., 1999; Libben, 2014; Marelli et al., 2012). Do they have one holistic entry (*goldfish*) or are they represented in a decomposed way, with separate entries for each of the compound's constituents (*gold* and *fish*), which are assembled for each use? The first aim of the present dissertation was to empirically investigate the lexical representation of noun-noun compounds in speech production and thus contribute to the understanding of the processing of compounds in speech production as well as the cognitive architecture of our language production system.

Previous studies have mainly used the picture-word-interference paradigm (PWI, e.g., Lorenz, Regel, et al., 2018; Lüttmann et al., 2011) or determiner-priming (Lorenz, Mädebach, et al., 2018) to investigate the representation of compounds. In those speech production paradigms, a visual or auditory prime (e.g., *moon*) precedes or accompanies the to-be-named target picture (*sunflower*), and it is assessed if and in what way the prime influences the speech production process of the compound. However, recent language production research suggests that the continuous picture naming paradigm might have several advantages over other paradigms, such as the ability to detect even small interference effects (e.g., Abdel Rahman & Melinger, 2019; Rose & Abdel Rahman, 2016) and no involvement of top-down control/ bias processes (e.g., Belke & Stielow, 2013). In the continuous picture naming paradigm, participants simply name a sequence of pictures that includes several members of different semantic categories, none of which appear in succession. There are no superimposed primes in this paradigm. Instead, it is assessed how the production of the preceding category member(s) influences the production of the following one(s). Studies have shown that participants' naming latencies within semantic categories linearly increase with each named category member, showing that the already named category members interfere with the production of the following ones. Although this cumulative semantic interference (CSI) effect has been extensively used as a tool to investigate different aspects of lexical-semantic encoding (e.g., Belke, 2013; Costa et al., 2009; Hoedemaker et al., 2017; Howard et al., 2006; Kuhlen & Abdel Rahman, 2017, 2021; Navarrete et al., 2021, 2010; Oppenheim, 2018; Oppenheim et al., 2010; Rose & Abdel Rahman, 2016, 2017; Runnqvist et al., 2012), the effect itself is not fully understood. It is, for example, still under debate at which level of the speech production system the effect originates, and which mechanism is responsible for the accumulation of interference (e.g., Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010; Roelofs, 2018). It is also unknown if and how the morphological structure of the produced words influences CSI. As we planned to use CSI to investigate the representation of compounds, understanding the mechanisms underlying the effect and how it is affected by the targets' structure is key to make precise predictions. Thus, the second aim of this dissertation was to close these knowledge gaps to gain a more comprehensive understanding of cumulative semantic interference.

In three studies, we first investigated cumulative interference behaviourally (Study 1) and electrophysiologically (Study 2) and then used the effect as a tool to investigate the lexical representation of compounds (Study 3). Before outlining the current research in more detail (Section 2), the following sections provide some relevant background on language production. Section 1.1 provides a short overview of the pre-articulatory planning stages in single word production. This section serves as the theoretical foundation for Section 1.2, in which theories of the lexical representation of compounds are introduced and key empirical evidence on the topic is discussed. Sections 1.3 and 1.4 describe cumulative semantic interference in more detail, before the research questions of the present studies are outlined in Section 1.5.

1.1. Pre-articulatory planning stages in single word production

At the heart of successful word production lies the lexical-semantic encoding process, namely the "translation" of a conceptual message into lexical entities shared among speakers of the same language community. While there are several language production models describing this process, they all converge on the following two assumptions: 1. Lexical-semantic encoding includes at least two levels, a conceptual and a lexical level, and 2. semantically related lexical entries are initially coactivated via the conceptual level before the target's entry is selected from this cohort of activated items. Here, the magnitude of co-activation is directly modulated by the degree to which the concepts are semantically related to the target concept, with stronger co-activation for closely related concepts (e.g., Caramazza, 1997; Dell et al., 1997; Levelt et al., 1999). The influential two-stage model proposed by Levelt and colleagues (1999) assumes two lexical levels, a lemma and a word form level (implemented as WEAVER ++ in Roelofs, 1992, 1997, 2008). At the lemma level, the word's syntactic properties are specified (including grammatical gender, number or tense). The (phonological) word form information, such as segmental and metrical information about the word, is stored at the word form level. According to this model, the production of a single word (e.g., the German word *Fisch*$_{\text{sing/masc}}$ [fish]) in a picture naming task is assumed to proceed as follows: The picture (fish) first activates the preverbal, conceptual information, before activation spreads to the corresponding lemma representation, containing information about the word's grammatical gender (masculine) and number (singular). Simultaneously, semantically related concepts and their lemma representations are coactivated due to spreading activation at the conceptual level (e.g., categorically-related concepts, like *whale* or *dolphin,* or semantic associates, such as *fin* and *water*; Collins & Loftus, 1975). As the activation spread is bidirectional, the coactivated lemmas further activate their concepts, resulting in reciprocal activation of related concepts and their lemmas. From this cohort of activated lexical representations, the target's lemma (as the most activated entry) is being selected, before the corresponding phonological word form (/fɪʃ/) can be retrieved (Levelt et al., 1999; see also Abdel Rahman & Melinger, 2009; Damian & Bowers, 2003; Dell et al., 1997; Mahon et al., 2007). While other models assume only one lexical layer (e.g., Caramazza, 1997; Schade, 1999), the research presented in this dissertation used the two-stage model (Levelt et al., 1999) as theoretical foundation and was thus built on the assumption that the lexical level consists of a lemma and a word form level.

1.2. Representation and processing of compounds

Noun-noun compounds are morphologically complex words that consist of two free-standing nouns (*toothbrush*: *tooth* & *brush*). In German, compounds are right-headed (e.g., Williams, 1981), that is, the rightmost constituent (i.e., the head) carries the syntactic properties of the whole compound (gender, number etc.) and, in case of a semantically transparent head, also its core meaning (a toothbrush is a brush), while the first constituent (i.e., the modifier) adds to this meaning (a toothbrush is a brush that is used for teeth). Here, semantic transparency describes the semantic relation between the compound and its constituents, namely to what extent the meaning of the constituents (*tooth* and *brush*) is maintained in the meaning of the compound (*toothbrush*). In transparent compounds (e.g., *toothbrush*) the meaning of both constituents is retained, whereas this is not the case in opaque compounds (e.g., *ladybird*; for more detail on semantic transparency and different ways to define it, see Günther & Marelli, 2019; Libben et al., 2003; Lorenz & Zwitserlood, 2016; Schäfer, 2018; Zwitserlood, 1994).

With regards to the lexical representation of compounds, the two-stage model described above (Levelt et al., 1999) assumes that compounds have a single, holistic lemma representation (TOOTHBRUSH) but morpheme-sized word form representations (/tuθ/ and /brəʃ/). In this single-lemma account, the morphological complexity of compounds is thus solely represented at the word form level. Others argue in favour of multiple lemma representations for compounds, with constituent lemma representations accompanying the holistic compound lemma (Marelli et al., 2012). In this case, the holistic compound lemma as well as the constituent lemmas must be selected during compound production before activation spreads to the constituent-sized word form representations. Thus, according to the multiple-lemma account, the morphological structure of compounds affects compound processing at the lemma as well as the word form level (for an alternative view on representations, see Baayen et al., 2019).

In line with both theoretical accounts, most empirical evidence suggests that compounds have decomposed representations on the word form level (e.g., Bien et al., 2005; Lorenz, Regel, et al., 2018; Lorenz & Zwitserlood, 2016; Lüttmann et al., 2011; Roelofs, 1996; but see Janssen et al., 2008, 2014). However, empirical research on the lemma representation of compounds is sparse and inconclusive (e.g., Lorenz, Mädebach, et al., 2018; Lorenz & Zwitserlood, 2016; Lüttmann et al., 2011; Marelli et al., 2012; Mondini et al., 2004; Semenza et al., 1997). Most studies with healthy adult speakers point towards a single compound lemma. For example, neither Lüttmann et al. (2011) nor Lorenz, Regel, et al. (2018) found evidence for the activation of constituent lemmas during compound production in the reaction time data of their PWI studies. In this picture naming task, a to-be named picture (e.g., of a *dog*) is presented alongside a to-be-ignored distractor word. It is well-documented that picture naming latencies are longer for semantically related (e.g., *mouse*) compared to unrelated distractors (e.g., *airplane*; Glaser & Düngelhoff, 1984). This interference effect is said to reflect lexical competition during lemma selection (e.g., Damian & Bowers, 2003; Glaser & Düngelhoff, 1984; Hantsch et al., 2005; Levelt et al., 1999; Schriefers et al., 1990; for an alternative explanation, see Mahon et al., 2007). In the PWI-studies investigating compound representation, the semantically related distractors were either related to the whole compound (e.g., distractor: *tulip* → target: *SUNFLOWER*) or to its modifier (e.g., distractor: *moon* → target: *SUNFLOWER*). While semantic interference was observed in the whole-compound condition, none was found in the modifier-condition. This suggests that the modifier lemma was not activated during compound production, as the semantically related distractor should have otherwise interfered (at least to some degree) with its selection and thus with the production of the whole compound. Converging evidence was also found in a determiner-priming study (Lorenz, Mädebach, et al., 2018). Here, compound production was faster when participants were presented a head-congruent determiner prime compared to a head-incongruent one, while no such priming effect was observed for modifier-congruent determiner primes. As this suggests that the gender information of the modifier constituent was not activated during compound production, the results were interpreted as evidence for the single-lemma account.

Empirical evidence in favour of multiple lemma representations in compound production comes mostly from neuropsychological studies with people with aphasia, more specifically with people with syntactic word category deficits. These speakers have difficulties processing a particular syntactic word category (e.g., verbs), a deficit that persists when naming compounds which contain that category (e.g., verb-noun compounds, such as *blowfish;* Lorenz et al., 2014; Mondini et al., 2004; Semenza et al., 1997; for evidence from reading aloud, see Marelli et al., 2012). As this suggests activated syntactic information of the compound's modifier during compound production, the observation points towards multiple lemma representations (e.g., Marelli et al., 2012). However, tentative evidence for the involvement of constituent lemmas has also been found in error data of healthy speakers in a PWI study (Lorenz, Regel, et al., 2018) or in reaction-time data of a PWI study testing for gender-congruency effects (Lorenz & Zwitserlood, 2016). One possible reason for the inconclusive results is that modifier-related effects are likely to be rather small, and thus harder to detect than, for example, compound-/head-related effects. As the multiple-lemma account assumes a hybrid representation of compounds, the constituents' lemma as well as the compound's lemma are activated. In PWI or determiner-priming experiments, any modifier-related prime/distractor (e.g., distractor: *moon* → target: *SUNFLOWER*) thus only affects the modifier lemma (*SUN*), whereas a compound-related prime/distractor (e.g., distractor: *tulip* → target: *SUNFLOWER*) affects the holistic compound lemma (*SUNFLOWER*) as well as the lemma of the compound's head (*FLOWER*). This likely results in a weaker interference effect for the former than the latter. Using a different experimental paradigm that allows to detect small effects could thus help shed light on the representation of compounds.

In recent years, the continuous picture naming paradigm with its large cumulative semantic interference effect (also known as cumulative semantic cost) has been extensively used to investigate different aspects related to speech production (e.g., Alario & Del Prado Martín, 2010; Belke, 2013; Canini et al., 2016; Costa et al., 2009; Hoedemaker et al., 2017; Howard et al., 2006; Kuhlen & Abdel Rahman, 2017, 2021; Navarrete et al., 2010, 2021; Oppenheim, 2018; Oppenheim et al., 2010; Riley et al., 2015; Rose & Abdel Rahman, 2016, 2017; Runnqvist et al., 2012; Schnur, 2014). In the process, it has been suggested that the paradigm is particularly suitable to detect smaller effects, as interference can be observed in isolation without concomitant facilitation (Abdel Rahman & Melinger, 2019; Rose & Abdel Rahman, 2016).

Therefore, Study 3 in the current dissertation aimed to use cumulative semantic interference as a tool to investigate compound production, as this could bring us closer to answering the question how compounds are represented at the lemma level.

In the following section, the CSI effect will be described in more detail, including aspects of the effect that are not fully understood yet and that were at the centre of Study 1 and 2.

1.3. Cumulative semantic interference

Cumulative semantic interference is a semantic context effect observed in the continuous picture naming paradigm. In this experimental paradigm, several members of different semantic categories (e.g., *bed, chair, table, wardrobe, sofa* for the category *furniture*) are presented in a seemingly random order for naming. The category members are separated by a variable number of unrelated objects (usually between 2 and 8– also called "lag"; Howard et al., 2006). These interleaved objects are either filler items or members of other semantic categories (example picture sequence including items of the category *furniture*: *<u>bed</u>, dog, tree, <u>chair</u>, cat, glass, bread, pencil, <u>table</u>, …*). Characteristically, participants' naming latencies within semantic categories increase in a linear fashion with each additionally named category member (e.g., Belke, 2013; Costa et al., 2009; Howard et al., 2006; Navarrete et al., 2010; Oppenheim, 2018; Oppenheim et al., 2010; Rose & Abdel Rahman, 2016, 2017; Runnqvist et al., 2012; Schnur, 2014). Initially it was assumed that this behavioural CSI effect is independent of the number of intervening (unrelated) items (e.g., Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010). However, a more recent study has shown that the CSI effect diminishes when the number of intervening items is continuously large (e.g., 8 intervening items or more, Schnur, 2014). Furthermore, several studies provided evidence that the CSI persists even when repeatedly naming the same items (e.g., Costa et al., 2009; Navarrete et al., 2010; Rose & Abdel Rahman, 2017).

All existing models explaining CSI agree that its locus, namely the level at which it comes into effect and behavioural consequences arise, is the lexical level (e.g., Abdel Rahman & Melinger, 2019; Belke, 2013; Howard et al., 2006; Navarrete et al., 2010; Oppenheim et al., 2010; Roelofs, 2018). There, it is interpreted as an increasing difficulty to select the target's lexical representation as the result of previously naming semantically related category members. However, the longevity and accumulating nature of CSI cannot be explained by the short-lived activation within the lexical system (e.g., Glaser & Düngelhoff, 1984). Therefore, it has been argued that the origin of CSI must be elsewhere (as opposed to its locus, mentioned above), with an additional mechanism responsible for the longevity of the effect (e.g., Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010; Roelofs, 2018). Both, the location of the origin and the actual mechanism underlying CSI, are still under debate.

According to some models explaining cumulative semantic interference, the effect originates at the interface of the conceptual and lexical level (Howard et al., 2006; Oppenheim et al., 2010). There, a learning mechanism causing long-lasting changes to the production system is responsible for the longevity of CSI. Howard and colleagues (2006) propose that the links between the target's conceptual and lexical representation are strengthened after successful lexical selection, a learning mechanism that renders the target more available for future naming (i.e., long-term repetition priming, see also Mitchell & Brown, 1988; Wheeldon & Monsell, 1992). When this concept is subsequently coactivated in the naming process of a semantically related category member, the strengthened links activate its corresponding lexical representation more strongly than those of other coactivated but previously unnamed items, making it a strong competitor in the lexical selection process of the to-be-named object. In the continuous picture naming paradigm, each named category member adds to the cohort of strongly activated lexical representations, rendering the lexical selection process of the to-be-named objects increasingly difficult. The result is accumulating interference within semantic categories. Oppenheim and colleagues (2010) agree with Howard et al. (2006) on the location of the learning mechanism but argue for an error-driven learning mechanism without lexical competition, where the links between conceptual features and lexical representations of coactivated non-targets are weakened in addition to the strengthening of the target's links.

Others argue for a purely conceptual origin of CSI (Belke, 2013; Roelofs, 2018). While Belke (2013) proposes a similar learning mechanism to Howard et al. (2006), she locates it at the connections between the conceptual features and the lexical concept (a unitary conceptual representation). After the successful naming of a target, these connections are strengthened, resulting in particularly strong conceptual coactivation of the target when subsequently naming a semantic relative with shared semantic features. This, in turn, also leads to strong activation of the previously named target's lexical representation, making it a strong competitor in the lexical selection process of the to-be-named relative. With each additionally named category member the competition increases, resulting in accumulating interference. In support of her argumentation, Belke (2013) presented evidence that cumulative effects can also be observed in purely conceptual tasks that do not (necessarily) involve the lexical level. In a semantic classification task, she presented participants with a seemingly random sequence of object pictures that included members of different semantic categories. Just as in the naming tasks, the category members were separated by multiple unrelated items. When she asked participants to classify these objects via button-press as either man-made or natural instead of naming them, she observed cumulative facilitation instead of cumulative interference, meaning participants' reaction times linearly decreased within semantic categories. Belke (2013) argues that repeatedly activating the semantic features related to either natural or man-made objects of a certain semantic category (e.g., the features *breathing* and *living* to identify members of the category *animals* as natural) leads to accumulating activation at the conceptual level, which renders the man-made/natural distinction within semantic categories increasingly easy. Furthermore, Belke demonstrated that cumulative interference and cumulative facilitation interact when interleafing picture naming and picture classification within the same experiment, which suggests that both effects share the same underlying mechanism (Belke, 2013, Exp.5). As the classification task (likely) only requires conceptual-semantic processing, she takes this as evidence that both cumulative effects share the same origin at the conceptual level. Roelofs (2018) also argues for a purely conceptual origin of cumulative interference but unlike Belke (2013), he proposes a temporary bias towards the target's concept after selection instead of long-lasting changes to the links between the target's lexical concept and its semantic features. In a computational simulation, he successfully modelled cumulative interference in picture naming as well as cumulative facilitation in a semantic classification task. According to Roelofs, the temporary bias more readily explains findings that suggest that cumulative interference disappears when lags between category members are consistently large (i.e., when the number of unrelated items between category members is consitently larger than eight; Schnur, 2014). He argues that these results show that cumulative interference is not as persistent as other long-lasting effects, such as repetition priming, as repetition priming can still be observed after several weeks (Mitchell & Brown, 1988). By this logic, Roelofs (2018) explains, cumulative interference and repetition priming cannot share the same long-term learning mechanism as suggested by Belke (2013) and Howard et al. (2006). So, while he agrees with Belke (2013) on the origin of the CSI effect, he argues for a different underlying mechanism that is responsible for the longevity of the effect.

The preceding section shows that there is still a great debate about the origin of cumulative interference. One way to advance this debate is to take a closer look at the cumulative facilitation effect observed in semantic classification (Belke, 2013). Cumulative facilitation is not easily explained by models assuming a learning mechanism at the lexical-semantic interface because they necessitate the involvement of the lexical level (Howard et al., 2006; Oppenheim et al., 2010), which is most likely not a prerequisite for semantic classification. This speaks in favour of a conceptual origin of the CSI effect (Belke, 2013; Roelofs, 2018). However, the reported cumulative facilitation effect has only been replicated once in a verbal version of the classification task (Riley et al., 2015) and not much is known about its relation to cumulative interference. Thus, more research on cumulative facilitation and how it is related to cumulative interference can help to close the knowledge gap related to the origin of cumulative interference.

Another question that has been left unanswered thus far is whether cumulative interference is influenced by the morphological structure of the targets used in the experiment. While CSI is clearly semantically driven, it is said to come into effect at the lexical level (Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010; Roelofs, 2018). Thus, lexical factors, such as the targets' morphology, might modulate the effect, particularly if the structure of the lemma representation of morphologically complex and simple targets differs (e.g., Marelli et al., 2012, see Study 3 in the current dissertation).

In order to close these knowledge gaps, Study 1 and 2 were designed to further investigate cumulative semantic interference. Because only when we have an extensive appraisal of the effect, can we and other researchers make informed predictions when using it as a research tool. To investigate the origin of cumulative interference, both studies further explored its relation to cumulative facilitation. This effect provides substantial support in favour of conceptual-origin accounts of CSI (Belke, 2013; Roelofs, 2018) but poses a problem for those assuming its origin at the lexical-semantic interface (Howard et al., 2006; Oppenheim et al., 2010). Thus, further investigating cumulative facilitation and its similarities and differences to cumulative interference can provide evidence that helps adjudicate between the two accounts. In Study 1, we investigated both context effects behaviourally and analysed, whether one effect can be used to predict the size of the other, as this would point towards a functional link between the two effects. Here, we also tested if CSI is influenced by the morphological structure of the targets, namely whether noun-noun compounds (*goldfish*, *king crab*, *hair jelly*) induce the same magnitude of interference as their simple noun counterparts (*fish*, c*rab*, *jelly*). In Study 2, we went one step further and employed event-related potentials (ERPs) observed in the continuous electroencephalogram (EEG) to investigate the electrophysiological signatures of cumulative interference and cumulative facilitation. Looking at their temporal dynamics and topographies can provide valuable insights into the mechanisms underlying both effects.

1.4 Electrophysiological signatures of cumulative context effects

EEG is a non-invasive method to measure electrical activity of the brain with a millisecond-to-millisecond temporal resolution (e.g., Gazzaniga et al., 2013). ERPs, namely prototypical electrophysiological responses to a specific stimulus (type) that are extracted from the continuous EEG, can thus provide precise temporal information of specific cognitive processes (Luck, 2014). This method is therefore ideal to investigate commonalities and differences of cumulative interference and cumulative facilitation by comparing their continuous internal processes.

Studies investigating the electrophysiological signature of cumulative interference are sparse (Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Llorens et al., 2014; Rose & Abdel Rahman, 2017). To date, two ERP components have been linked to the effect: First, an enhanced posterior positivity between around 200 and 400 ms after picture onset, which linearly increases with each named category member and is positivity correlated with reaction times (Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017; but see Llorens et al., 2014). This component is said to reflect increasing difficulty during lexical selection. Its onset roughly corresponds to the onset of lexical selection estimated in meta-analyses (Indefrey & Levelt, 2004; Indefrey, 2011) and is comparable to results found in speech production studies investigating lexical access with a different paradigm (e.g., Aristei et al., 2011; Bürki, 2017; Strijkers et al., 2010). The second component that has been linked to cumulative interference by some studies is a negativity at posterior sites that, too, increases with each named category member (Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017; but see Costa et al., 2009; Llorens et al., 2014). This late negative component has been cautiously interpreted as one from the N400 family, a well-established electrophysiological indicator of conceptual-semantic processing usually peaking around 400 ms at centro-parietal sites (Kutas & Federmeier, 2011; Kutas & Hillyard, 1980). In the context of cumulative interference, it has been tentatively suggested that this ERP could reflect the learning mechanism responsible for the longevity of cumulative interference (Rose & Abdel Rahman, 2017), namely the strengthening of connections between the conceptual and lexical level (Howard et al., 2006; Oppenheim et al., 2010) or between semantic features and lexical concepts (Belke, 2013). However, due to inconsistent results it is still unclear if this late negativity is part of the neurocognitive signature of cumulative interference at all. While Rose and Abdel Rahman (2017) found a correlation between this component and the behavioural data between 460 and 590ms post picture onset, pointing to a clear link between this component and CSI (see also Kuhlen & Abdel Rahman, 2021), no such modulation was found in other CSI studies (Costa et al., 2009; Llorens et al., 2014). Thus, further research is necessary to provide a clear picture of the electrophysiological underpinnings of cumulative interference.

As far as I am aware, no study has as yet investigated the electrophysiological signature of cumulative facilitation. However, semantic priming, the mechanism behind facilitation, has been extensively studied. Studies with different kinds of stimuli (e.g., pictures, sounds, visual words, auditorily presented words) and different kinds of tasks (e.g., picture naming, semantic judgement/classification), have consistently linked semantic priming to an attenuated N400 (e.g., Blackford et al., 2012; Bürki, 2017; Geukes et al., 2013; Kutas & Federmeier, 2011; McPherson & Holcomb, 1999; Piai et al., 2014; Rabovsky et al., 2021; Rose et al., 2019). The N400 is a negative modulation with a central-parietal scalp distribution that peaks around 400ms post-stimulus onset. It is typically enhanced when a target appears in an incongruent or semantically unrelated context compared to a neutral one, and its amplitude decreases with congruency. Here, the decrease of the N400 is assumed to reflect easier access to the target's semantic information due to semantic priming by the prime stimulus or the congruent sentence context (for a detailed discussion of the N400, see Kutas & Federmeier, 2011). For example, in non-verbal picture-picture priming studies, the widely distributed N400 component on the target (e.g., *dog*) is smaller (i.e., reduced) when the target is preceded by a semantically related prime picture (e.g., *cat*) compared to an unrelated one (e.g., *wardrobe*, McPherson & Holcomb, 1999). Similarly, in studies employing a non-verbal semantic classification task (natural/man-made distinction), a reduced N400 effect at temporo-parietal sites can be observed for pictures following a semantically related compared to an unrelated word (EEG: Geukes et al., 2013; MEG: Dobel et al., 2010). Thus, the N400 component is a well-established electrophysiological indicator for conceptual-semantic processing, with its magnitude reflecting the ease to access and/or integrate semantic information.

1.5 Aims and outline of the present work

The aim of the present dissertation was two-fold. The first aim was to investigate the lemma representation of noun-noun compounds in speech production to add an additional piece to the puzzle that is the cognitive architecture of our language production system and better understand compound processing in speech production. As we planned to use cumulative semantic interference as a proxy for lexical processing, the second aim of this dissertation was to gain a more comprehensive understanding of CSI and its modulating factors before using it to investigate compounds.

To that end, we conducted three continuous picture naming studies, which are at the centre of this dissertation. Study 1 and 2 aimed to further investigate cumulative semantic interference. Study 1 first explored if the morphological complexity of the targets is a factor that modulates CSI. This is particularly essential for studies wanting to use compounds as targets (Study 3). It then investigated the origin of CSI by exploring its relation to cumulative facilitation, a cumulative context effect found in purely conceptual classification tasks.

Study 2 also investigated the relation between cumulative interference and cumulative facilitation to advance the discussion on the origin of cumulative context effects. However, in this study the continuous EEG was recorded alongside the behavioural responses to compare the mental chronometry and topography of both context effects. Based on the results of Study 1, it was also investigated how target repetitions modulates the CSI effect.

In Study 3, the CSI effect was used as a tool to investigate the lemma representation of compounds in speech production. The aim was to better understand the processing and representation of compounds in speech production and thus provide further insights into the structure of our language production system as well as the production of complex words.

All participants who took part in the three studies were healthy adults between the age of 18 and 35, who reported to be German native speakers. All experiments were conducted in German.

In the following sections, I will first describe the three studies in more detail, before jointly discussing the findings and the implications that can be drawn from them.

2. Summary of the present studies

2.1 Study 1: Cumulative semantic interference is blind to morphological complexity and originates at the conceptual level

Study 1 tried to fill some of the knowledge gaps related to cumulative interference by investigating 1. if cumulative interference is modulated by morphological complexity, and 2. where in the speech production system the effect originates. We explored both issues in two behavioural experiments with the same material and the same group of participants (N = 36).

Experiment 1 used a continuous picture naming task to test whether morphologically complex noun-noun compound targets (*goldfish*, *hair jelly*, …) induce the same magnitude of cumulative interference as their simple noun counterparts (*fish*, *jelly*, …). The picture stimuli (N = 90) belonged to 18 different semantic categories (furniture, marine animals, clothing …) and were selected in such a way that they could equally well be named with either a compound noun or a simple noun (*hair jelly* / *jelly*). This was empirically verified in a separate rating study with another group of participants. In the main experiment, participants learnt the corresponding names of the objects in a familiarisation phase, in which they were asked to overtly name the pictures. Each participant was presented with five experimental lists (Repetition 0,1,2,3,4) to enhance statistical power and further investigate the effect of item repetition on cumulative interference.

The results revealed a CSI effect of similar magnitude for compounds and simple nouns, indexed by a systematic increase of naming latencies within semantic categories. This suggests that morphological complexity is not a factor modulating cumulative interference. In line with previous studies, we did not observe a direct influence of item repetition on the CSI effect (e.g., Costa et al., 2009; Navarrete et al., 2010; Rose & Abdel Rahman, 2017) but found that long lags (i.e., a greater number of intervening items between category members) induced weaker interference after several repetitions, suggesting that the CSI effect was not completely unaffected by the factor repetition.

Experiment 2 employed a semantic classification task to investigate cumulative facilitation and its relation to cumulative interference, and to explore whether the two context effects can predict one another, which would point to a common conceptual origin (Belke, 2013). The same participants saw the same picture stimuli as in Experiment 1 and were instructed to classify the depicted objects as either man-made or natural (via button-press). When selecting the picture stimuli, we ensured that they contain an equal number of man-made and natural entities. Like in Experiment 1, participants completed five experimental lists (Repetition 0,1,2,3,4) to investigate the influence of item repetition on cumulative facilitation.

The results revealed that participants' response latencies systematically decreased with each classified picture within a given semantic category. However, the effect was strongly influenced by repetition. We found a strong facilitation effect in the first classification instance (Repetition 0) but only weak or no cumulative facilitation in the repetitions (Repetition 1-4). This replicates the cumulative facilitation effect reported by Belke (2013) but additionally shows that cumulative facilitation is strongly affected by item repetition. Our results thus provide corroborating evidence for cumulative context effects in purely conceptual tasks. Moreover, in an additional analysis we found that the size of the interference effect observed in Experiment 1 (i.e., reaction time difference between the first and the last category member) can predict the size of the facilitation effect observed in Experiment 2. This points to a strong link between the two effects and suggests that both share the same underlying mechanism (e.g., Donders, 1969). The results observed in Experiment 2 are predicted by models that argue for a purely conceptual origin of cumulative interference (and cumulative facilitation, Belke, 2013; Roelofs, 2018). In contrast, they are not as easily explained by models that locate the origin at the interface between the conceptual and lexical level (Howard et al., 2006; Oppenheim et al., 2010). This is because the lexical level is not (necessarily) involved during the classification task, thus a learning mechanism at the links between the conceptual and lexical representation would not predict cumulative facilitation (see Belke, 2013).

To summarise, Study 1 revealed four key findings: 1. CSI is identical for morphologically complex noun-noun compounds and morphological simple nouns, suggesting that morphological complexity is per se not a modulating factor of CSI. 2. Cumulative effects can also be observed in purely conceptual tasks, expressed as cumulative facilitation. 3. Cumulative interference can be used to predict cumulative facilitation. 4. Cumulative facilitation is more strongly influenced by the factor repetition than cumulative interference but both effects are affected by repeatedly seeing the same items. Overall, the results of Study 1 point to a purely conceptual-semantic origin of cumulative interference and cumulative facilitation.

2.2. Study 2: The electrophysiological signatures of cumulative semantic interference and facilitation point to a common conceptual origin

While Study 1 compared cumulative interference and cumulative facilitation on a behavioural level, Study 2 went one step further and looked at the associated brain activity. The aim of this study was to gain a more comprehensive understanding of the commonalities and differences between the two context effects by comparing their electrophysiological signatures. Looking at their temporal dynamics as well as their topography allows us to better understand their relation and thus contributes to the discussion of their origin. While very few studies have looked at the electrophysiological signature of cumulative interference (Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017), none have investigated the brain response linked to cumulative facilitation. Based on the results of Study 1, an additional aim of this study was to better understand the influence of item repetition on both context effects.

The design of this study was very close to that in Study 1. We recorded the continuous EEG while participants (N = 36) first completed a continuous picture naming task (Experiment 1) and then a semantic classification task (Experiment 2). The picture stimuli (N = 90) belonged to 18 different semantic categories and were identical to the (monomorphemic) stimuli used in Study 1. In a familiarisation phase, participants briefly studied the pictures and the corresponding names on a sheet of paper. In Experiment 1, participants were presented three experimental lists (Repetition 0,1,2) and were asked to overtly name the pictures. In Experiment 2, participants also completed three experimental lists (Repetition 0,1,2), this time classifying the depicted objects as either man-made or natural (via button-press).

Based on previous continuous naming studies, we predicted a behavioural CSI effect in Experiment 1 (e.g., Belke, 2013; Belke & Stielow, 2013; Howard et al., 2006; Oppenheim et al., 2010; Rose & Abdel Rahman, 2016, 2017), most likely independent of the factor repetition (e.g., Costa et al., 2009; Navarrete et al., 2010; Rose & Abdel Rahman, 2017). Furthermore, we expected the behavioural CSI effect in all repetitions to be mirrored by a posterior positivity starting around 200 or 250 ms post picture onset and possibly by a negative modulation starting around 450 ms in the same location

(Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017). In Experiment 2, we expected to replicate the behavioural results observed in Study 1, namely cumulative facilitation in the form of decreasing reaction times within semantic categories (see also Belke, 2013), and expected the effect to interact with repetition. In the electrophysiological data, we predicted that cumulative facilitation would be mirrored by a reduced N400 for later category members compared to earlier ones, reflecting the increasing ease to access semantic information within semantic categories (e.g., Geukes et al., 2013; Kutas & Federmeier, 2011). Based on the assumption that the posterior negativity in continuous naming indeed reflects the learning mechanism behind cumulative interference (Rose & Abdel Rahman, 2017), we also hypothesised to find a similar component in the continuous classification task in Experiment 2.

Results confirmed the predicted pattern, with two exceptions. In Experiment 1, we observed CSI behaviourally but contrary to results in Study 1 found it to decrease with repetitions. In the EEG, we found the expected posterior positivity from around 250 to 400ms as well as the posterior negativity from around 450 to 600 ms post picture onset. Reflecting the behavioural data, both ERP components were influenced by repetition. The positive modulation decreased with repetitions, while the negative one increased. This contradicts results reported by previous studies that did not find an influence of repetition on these ERP components (Costa et al., 2009; Rose & Abdel Rahman, 2017). The posterior positivity is interpreted to reflect lexical retrieval (e.g., Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017). The function of the posterior negativity is less clear. As we found a similar component in Experiment 2, I will discuss its function below.

In Experiment 2, we observed cumulative facilitation behaviourally and found it to be affected by the factor repetition. We found strong facilitation in the first classification cycle (Repetition 0), none in the second (Repetition 1) and weak facilitation in the last (Repetition 2). This was mirrored by the electrophysiological data. Cumulative facilitation was indexed by a positive modulation at posterior sites between 350 and 400ms in the first classification cycle (Repetition 0), while no such modulation was observed in the other two repetitions. The positivity is interpreted as the predicted reduced N400 (e.g., Geukes et al., 2013; McPherson & Holcomb, 1999), and is assumed to reflect the increasing ease with which semantic information is accessed/integrated (e.g., Kutas & Federmeier, 2011). In addition, we observed a posterior negativity between 450 and 600 ms which was not influenced by repetitions. As its spatial and temporal distribution is comparable to the negativity found in Experiment 1, we assume that the two modulations reflect the same ERP component and thus the same underlying cognitive process(es). This component has previously been interpreted to reflect the learning mechanism responsible for the CSI effect (Rose & Abdel Rahman, 2017). The fact that we found it in both experiments provides additional support for this interpretation. In an additional analysis we also showed that the behavioural cumulative interference effect could be used as a predictor for the behavioural cumulative facilitation effect, thereby replicating Study 1. This, too, suggests that both effects share an underlying mechanism.

Overall, the results of Study 2 revealed that the electrophysiological signatures of cumulative interference and cumulative facilitation are very similar in their temporal dynamics and spatial distribution and that both effects are influenced by the factor repetition. These commonalities, as well as the fact that one effect can predict the other, suggest that both effects are functionally linked and, in turn, that they share a common conceptual origin (Belke, 2013; Roelofs, 2018).

2.3. Study 3: On the Lexical Representation(s) of Compounds: A Continuous Picture Naming Study

Now that we have a more comprehensive understanding of the CSI effect (Study 1 and 2) and know that the morphological structure of the targets has no specific influence on the effect (Study 1), we can make informed predictions when using it as a research tool (Study 3). The aim of Study 3 was to use CSI to investigate whether compounds have a single holistic lemma representation (Levelt et al., 1999) or multiple representation, namely separate lemma representations for the constituents in addition to the holistic compound representation (Marelli et al., 2012).

In our continuous picture naming experiment, categorical membership of the picture stimuli in the compound condition (N = 90) was established solely through the compounds' first constituents (e.g., category animals: *Eselsohr* (lit. donkey ear - dog ear in a book), *Zebrastreifen* (zebra crossing), *Pferdeschwanz* (lit. horsetail – ponytail), *Mausefalle* (mouse trap), *Katzenstreu* (cat litter)).

Importantly, the compounds themselves were not semantically related. This was verified in a separate semantic similarity rating with a different group of participants. In addition, pictures depicting the compounds' first constituents were presented as a control condition (*Esel* (donkey), *Zebra* (zebra), *Pferd* (horse), *Maus* (mouse), *Katze (*cat)). Based on previous continuous picture naming studies, we predicted strong cumulative interference in the simple noun control condition, as these category members were semantically related (e.g., Howard et al., 2006). For the compound condition, we had two hypotheses: If compounds have multiple-lemma representations, we expected the lemma representations of the compounds' first constituents to interfere with one another within semantic categories, thus delaying the production of the whole compound. In this case, we predicted weaker interference in the compound than in the control condition, as the latter is a whole-word effect while the former is a partword effect. However, if compounds are represented in a single, holistic lemma representation, we expected to observe no interference effect, as the compounds as a whole were not semantically related and should therefore not interfere with one another during lexical selection. Participants were presented with five experimental lists to enhance statistical power (Repetition 0,1,2,3,4). We also included a measure of semantic transparency into the analysis to account for variability of this variable in our items. The transparency values for the items were obtained in a separate rating study with another group of participants (N=20). Here, participants evaluated the semantic relation between each of the two constituents of the compound and the compound itself on a six-point Likert scale (e.g., for the item *football*: *The meaning ball is included in the meaning of football* and *The meaning of foot is included in the meaning of football*, see also Lorenz & Zwitserlood, 2014).

The results revealed cumulative interference in the control as well as in the compound condition and showed that both were equally influenced by repetition. As predicted, the effect was stronger in the control than in the compound condition (15 ms vs. 9 ms mean increase in reaction times from one category member to the next). This is thus the first study to provide evidence from reaction time data that constituent lemmas are activated when unimpaired speakers produce a compound word. Our results therefore point towards a multiple-lemma representation of compounds (e.g., Marelli et al., 2012). We did, however, also find an influence of semantic transparency on the interference effect. This tentatively suggests that opaque compounds, namely those where the meaning of the constituents is not (fully) retained in the meaning of the compound (*hedgehog*, *butterfly*), might be represented in a single lemma representation instead.

3. General Discussion

The findings outlaid in the present dissertation advance our understanding of several speech production processes as well as the architecture of the speech production system. On the one hand, this dissertation provides valuable insights into semantic context effects, which will enable researchers to make more informed predictions in the future when using them as a tool to investigate speech production. On the other hand, it advances our understanding of the processing and representation of compounds in speech production and thus brings us one step closer to understanding the structure of the language production system.

The main aim of Study 1 and 2 was to gain a more comprehensive understanding of the cumulative semantic interference effect, in particular with regards to its origin. To do that, we investigated the commonalities and differences between cumulative interference and cumulative facilitation, as the relation of the two has been used to argue for a purely conceptual origin of cumulative context effects (Belke, 2013). We found that both context effects are modulated by the same factors (e.g., repetition) and that they are reflected by similar ERP components. In addition, we found that one behavioural context effect can be used to predict the other. Taken together, the results of Study 1 and 2 suggest a strong functional link between the two effects and thus point to a shared origin at the conceptual level. Study 1 additionally revealed that cumulative semantic interference is not influenced by the morphological structure of the items, meaning morphologically complex compounds induce cumulative interference of a similar magnitude as morphologically simple items. Study 3 built on this knowledge and used the CSI effect as a tool to investigate the lemma representation of noun-noun compounds. Here, we found clear evidence that the lemmas of the compounds' constituents are activated during compound production. The data thus point to a complex multiple-lemma representation of compounds, consisting of the holistic compound lemma and the constituent lemmas (Marelli et al., 2012). This finding thus reveals that morphological complexity already affects the lemma level of speech production and therefore contributes to our understanding of the architecture of our language production system.

In the following, I will first discuss factors modulating cumulative interference (3.1) and then outlay the implications our studies have on the discussion about the origin of cumulative interference (3.2). Lastly, I will integrate the findings on the representation of compounds into the existing literature and discuss their implication for the structure of our speech production system. Limitations of the present research as well as future directions will be discussed along the way.

3.1 Factors modulating cumulative semantic interference

To be able to make informed predictions when using cumulative interference as a research tool to investigate speech production it is necessary for us to understand factors that modulate the effect. Only then can we separate the influence of these factors from the effect of our experimental manipulation in the data and draw correct inferences from the results. The current dissertation provides valuable insights into two factors that (do not) modulate cumulative interference.

Morphological complexity

Compounds are commonly used alongside simple nouns in continuous picture naming studies (e.g. Belke, 2013; Costa et al., 2009; Howard et al., 2006; Kuhlen & Abdel Rahman, 2017; Rose & Abdel Rahman, 2016, 2017). More importantly, we planned to use the CSI effect to investigate the representation of compound targets (Study 3). Thus, understanding if and how the morphological complexity of targets influences CSI was essential to correctly analyse and interpret the results. Study 1 investigated this question and showed that the magnitude of CSI does not differ for morphological simple nouns (*shelf*, *bed*) and morphologically complex noun-noun compounds (*bookshelf*, *canopy bed*) when accounting for differences in semantic similarity. This is in line with results from a PWI study which reported identical interference for compound distractor-target pairs (wooden spoon—bread knife) and simple noun distractor-target pairs (spoon—knife; Lüttmann et al., 2011). The CSI effect in the compound condition was apparently mainly driven by the semantically related head constituent, whereas any activation that might have dissipated via the semantically unrelated first constituent did not significantly reduced the effect. Thus, future continuous picture studies can theoretically (continue to) mix morphologically simple and complex targets without having to fear additional effects due to the morphological structure of the targets. However, one needs to be cautious: Study 3 revealed that the lemma representations of the compounds' constituents are activated during compound production. This means that seemingly unrelated first constituents (*book* in *bookshelf* (category *furniture*)) could interfere with items and/or item constituents from other semantic categories (e.g., the item *folder* of the category *stationary items,* or the first constituent in *magazine subscription*). Thus, to avoid additional noise in the reaction time pattern, researchers might want to avoid including compounds in their stimuli set or control for semantic relatedness of all constituents. Important for this dissertation, Study 1 revealed that the morphological complexity of compounds per se does not influence the CSI effect. Thus, any effect we observed when using CSI to investigate the representation of compounds (Study 3) cannot simply be attributed to their complexity per se but is related to the semantic relation of the constituents.

Repetition

All three studies presented in this dissertation provide converging evidence that cumulative semantic interference is influenced by the factor repetition, both on a behavioural and electrophysiological level. In Study 2, the behavioural CSI effect decreased significantly after the first naming instance (Repetition 0: 129ms, Repetition 1: 34ms (RT difference between first and last category member)). In Study 3 we observed a similar pattern. Cumulative interference decreased with each repetition in both word type conditions (simple nouns: Repetition 0: 73ms, Repetition 4: 34ms; Compounds: Repetition 0: 58ms, Repetition 4: 34). In Study 1 we found no direct interaction between repetition and the behavioural CSI effect but found that CSI decreased in long-lag trials after several repetitions (i.e., when category members were separated by many (e.g., 8) unrelated items). This suggests that cumulative interference was weakened by repeatedly naming the same items, as it did not "survive" long gaps (i.e., many intervening items) between category members (for corroborating evidence concerning long lags, see Schnur, 2014). The fact we did not find a direct modulation of cumulative interference by the factor repetition in Study was likely due to the way in which the familiarisation phase was conducted. While participants in Study 2 simply studied the pictures and the corresponding names on sheets of paper, participants in Study 1 saw the stimuli in a random order on screen and were instructed to overtly name the depicted objects. This was done to ensure participants did not make an excessive number of mistakes on the morphologically complex target words (noun-noun compounds, e.g., *apple tree*, *canopy bed*, *index finger*). The first naming instance in Study 1 was therefore during the familiarisation phase, which was not recorded. Consequently, the reported first naming instance in Study 1 was actually the second, making it impossible to know whether interference decreased after the first naming instance like it did in Study 2. However, the fact that we found interference decreasing in long-lag trials after several repetitions in Study 1 shows that repetition had an effect on CSI. The electrophysiological data provide corroborating evidence that the CSI effect is affected by repetition. Both ERP components linked to cumulative interference, the posterior positivity and the posterior negativity, were modulated by repetition. Thus, taken together, the results of all three studies show that cumulative interference can be observed even after multiple repetitions, but that its magnitude decreases when repeatedly naming the same items. While this conclusion is also supported by a mega-analysis on semantic interference in social settings that is currently in preparation (Holtz et al., n.d.), it contrasts the results reported by earlier continuous picture naming studies (e.g., Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Navarrete et al., 2010; Rose & Abdel Rahman, 2017). None of them reported an interaction of repetition and cumulative interference. Yet, a closer look at some of these studies' descriptive data suggests that CSI observed in those studies might not have been completely unaffected by repetition effects either (e.g., Navarrete et al., 2010, p. 282: Repetition 0: 74ms, Repetition 1: 57ms, Repetition 2: 54ms, Repetition 3: 44ms; Rose & Abdel Rahman, 2017: Repetition 0: 52ms, Repetition 1: 50ms, Repetition 2: 36ms). While the descriptive data are, of course, not as informative as the statistical analysis and should therefore not be overinterpreted, they can serve as an indicator for a direction. More importantly, however, in Study 2 we also reanalysed the data from Rose and Abdel Rahman (2017) using a linear mixed model and found a significant influence of repetition on the interference effect. Thus, presumably, the more flexible but robust linear mixed model is more suitable to detect interactions with repetition than the repeated-measures ANOVAs used by previous studies (see, e.g., Baayen et al., 2008).

However, there is, of course, also the possibility that there are other factors that influence the interaction between repetition and the CSI effect. We recently conducted a version of Study 3 with participants with aphasia (PWA) and a control group consisting of healthy adult speakers to investigate the lemma representation of compounds in PWAs (Lorenz et al., n.d.). At this point, we only analysed the data of the simple noun control condition. Preliminary results for the simple nouns suggest no interaction of repetition and CSI in the healthy control group, which stands in contrast to the results presented in this dissertation. One obvious difference between that study and the ones reported in this dissertation is the factor age. The average age of the healthy control group was significantly higher (56 years, min. 30, max. 73) than in any study reported in this dissertation (Study 1: 27 years; Study 2: 27 years; Study 3: 26 years). This, however, was likely not the only factor influencing the interaction of repetition and CSI. Recently, we also conducted a version of Study 3 with older participants (average age: 70 years, min. = 60, max. = 83) and a young control group (27 years) to test whether the lemma representation of compounds changes with age (Döring et al., n.d.). Preliminary results of the simple noun data in that study suggest an influence of repetition on the CSI effect in both participants groups, the older and younger speakers. This corroborates the results presented in this dissertation but also shows that the factor age is likely not the only factor responsible for the missing interaction between repetition and CSI in the control group in Lorenz et al. (n.d.). So, while evidence for the influence of repetition on the CSI effect is mounting (Study 1-3 in this dissertation, meta-analysis by Holtz et al. (n.d.), re-analysis of the data by Rose & Abdel Rahman (2017), study with older participants (Döring et al., n.d.)), the inconsistent results (e.g., Costa et al., 2009; Lorenz et al., n.d.; Navarrete et al., 2010) clearly show that we do not yet understand all factors that modulate this interaction. Thus, future research is necessary to continue to close this knowledge gap. Until then, future studies using CSI as a tool might want to take the likely influence of repetition on CSI into consideration when planning and analysing their experiments.

More importantly, however, all models explaining cumulative interference will have to integrate these findings and, if necessary, adapt them to account for the influence of repetition on the CSI effect (e.g., Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010; Roelofs, 2018). To date, none of the models explicitly addressed repetition effects on CSI because they had not been reported. In the following, I will thus hypothesise which models, based on their current specifics, could explain the repetition effects and which models might have difficulties doing so. While some models assume that long-lasting repetition priming and cumulative interference are related (Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010), others argue that they are two distinct effects that do not have the same origin (Roelofs, 2018; for empirical evidence, see Hughes and Schnur, 2017). The first type of models, namely those that argue for a link between cumulative interference and long-lasting repetition priming as well as a competitive lexical selection process (e.g., Belke, 2013; Howard et al., 2006), could, in my view, readily explain the observed result pattern. Here, the increased activation of the target through repetition priming might lead to a weaker build-up of cumulative interference within semantic categories as the competition between semantically related items might be resolved faster than without repetition priming (i.e., when naming the object for the first time). In contrast, for non-competitive models it might be more difficult to explain the observed repetition effects (Oppenheim et al., 2010, see also Navarrete et al., 2010). If repetition priming and cumulative interference are linked and cumulative interference is the result of weakened links between conceptual and lexical representations of non-targets and strengthened ones for targets, then repetition priming (i.e., the main effect for repetition, independent of CSI) should be negatively affected in the continuous picture naming paradigm. In other words, it should either not be observed or at least be attenuated. This is because the weakened links between the target's features and its lexical representation (e.g., *dog*) as a result of naming a semantically related category member later on (*cat*) should lead to longer naming latencies when later naming the target for the second time (*dog*). Repetition priming (i.e., the main effect of repetition, independent of CSI) should thus be attenuated compared to a situation in which no other category member was named and thus the links between the target's features and its lexical representation (*dog*) were not weakened. This is unless the strengthened links between the target's lexical representation and its unique features (i.e., those features it does not share with other category members, e.g., “barks” for the target *dog*) are enough to induce long-lasting repetition effects. One way to test whether my predictions for these error-driven models are correct would be to systematically manipulate feature overlap between category members and to investigate whether this modulates the main effect of repetition. The third type of model, namely competitive models that do not assume that cumulative interference is linked to long-lasting repetition priming but instead is the result of a more temporary bias, would also be able to explain the observed result pattern (Roelofs, 2018). In this case, long-lasting repetition priming would add to the effect of the temporary bias, making the concept even more readily available. This availability would result in faster lexical selection as the difference in activation between the target and related competitors is larger than without general repetition priming. As mentioned above, this might lead to a weaker build-up of interference within semantic categories as the competition between semantically related items might be resolved quicker than without repetition priming.

Thus, all three types of models could potentially explain the interaction between repetition and cumulative interference we observed in the three studies. However, it is clear that until these findings are computationally implemented, these remarks remain hypotheses.

3.2 On the origin of cumulative semantic interference

The behavioural and electrophysiological data reported in Study 1 and 2 consistently point to a strong functional link between cumulative interference in picture naming and cumulative facilitation in semantic classification, which suggests that both effects share an underlying mechanism. As cumulative facilitation is a purely semantic effect, this shared mechanism is likely located at the conceptual level. Our results thus point to a purely conceptual origin of cumulative semantic interference (Belke, 2013; Roelofs, 2018). This conclusion is based on three key findings, which I will outline in the following.

Cumulative context effects in purely semantic tasks

Study 1 and 2 showed that cumulative context effects, in form of cumulative facilitation, can be observed in a purely semantic classification task (Experiment 2 in both studies). This replicates findings reported in the literature (Belke, 2013; see also Riley et al., 2015 for results from verbal classification) and thus provides corroborating evidence that cumulative context effects can also arise in tasks that do not necessitate the involvement of the lexical level. This, in turn, points to a purely conceptual origin of cumulative context effect, including cumulative semantic interference (Belke, 2013; Roelofs, 2018). Models locating the origin of CSI at the interface of the conceptual and lexical level cannot provide such a parsimonious explanation for these results (Howard et al., 2006; Oppenheim et al., 2010), as I will discuss in more detail at the end of this chapter.

Cumulative interference can predict cumulative facilitation

The second key finding that points to a purely conceptual origin of cumulative interference comes from joint analyses of cumulative interference and cumulative facilitation. In Study 1, we found that the behavioural CSI effect can be used as a predictor of the behavioural facilitation effect, and we were able to replicate this finding in Study 2. This suggests that both effects are the result of the same underlying mechanism. After all, one would not expect that one behavioural effect can predict the magnitude of another, completely unrelated one (e.g., Donders, 1969). In both studies, we found that stronger interference in the naming task predicts weaker facilitation in the classification task. While this suggests a functional link between the two effects, the direction of the predictive effect was initially rather surprising and not what we predicted. Based on the working model proposed by Belke (Belke, 2013), we initially predicted mirroring effects, namely that stronger interference predicts stronger facilitation. This prediction was built on the rationale that the effect in the naming task was based on conceptual facilitation that turned into interference at the lexical level, and that this facilitation would be identical to the facilitation found in the classification task, as we used the same experimental items and the same participants. In hindsight this seems to have been an oversimplification of the actual processes and there are multiple explanations for the observed pattern, based on Belke’s working model (2013).

First, the facilitation found in the classification task is likely not identical to the conceptual facilitation responsible for the lexical interference in the naming task because the task requirements differ. Successfully naming a picture requires fine-grained, deep processing of all semantic features of that target, particularly its unique features that it does not share with other category members (e.g., "has a trunk" for the target *elephant* or "has stripes" for the target *zebra*). Only then can the target be successfully distinguished from other coactivated category members and the correct lexical entry be selected. After successful naming of the target, the links between the features, particularly its unique ones, and the target's lexical concept would be strengthened, making it a strong competitor in the subsequent naming process of a to-be-named category member (CSI effect). Thus, in picture naming, deep semantic processing is key to perform the task. In the classification task, on the other hand, it is necessary to activate those features that identify an entity as either belonging to the man-made or natural category (e.g., "is an animal" for *elephant* and *zebra*). As these are shared by all category members, it is the shared category features that are essential to perform the classification task. Here, fine-grained semantic processing is not only not essential to perform the task (Belke, 2013; Riley et al., 2015), but quite possibly even disadvantageous as it may delay the response. Thus, the activation patterns at the conceptual level are likely not identical in both tasks, despite using the same experimental items and the same participants. This might explain why our initial prediction of strong interference predicting strong facilitation did not pan out.

The second possible explanation for stronger cumulative interference predicting weaker facilitation might be the results of the order in which the two tasks were performed. In both of our studies the classification task always followed the naming task. We did not alternate the tasks, as we also investigated the factor repetition and were thus keen to keep the number of repetitions within and between the tasks stable across all participants. Yet, this order might have directly influenced the way in which cumulative interference predicts cumulative facilitation. As just described, find-grained semantic processing is necessary to perform the picture naming task and successful naming of a target results in strengthened links to all its features. In the following classification task, however, the strengthened links to the unique features would attenuate the facilitation effect, as they hinder rather than facilitate the natural/ man-made decision. Thus, classification latencies increase, resulting in a decreased facilitation effect. Consequently, categories that induced strong interference because members have a lot of unique features, would then induce weaker facilitation than if the target had not previously been named (and no unique features had previously been strengthened). This corroborates previous findings by Belke (2013) who showed that cumulative interference and cumulative facilitation interact with one another when alternating picture naming and semantic classification in one experiment. Importantly, she observed an attenuated facilitation effect in trials that followed a successful naming trial (Belke, 2013, Exp.5). So, although Belke (2013) showed the direct cross-talk between the two effects in one experiment, while we observed the two effects in isolation and then related them statistically, our results converge. It is therefore likely that the task order had a direct influence on the way interference observed in the naming task predicted the facilitation in the classification task. However, to be certain that there is no other explanation for the observed direction of the prediction, it would be desirable to analyse data from experiments completed in the reversed order to verify our hypothesis about the factor task order. Alternatively, one could also look at the semantic features of the items, more specifically at the unique ones, and statistically verify our hypothesis. Semantic categories in which the category members have a lot of unique features should show stronger interference but weaker facilitation than those with fewer unique features.

So, the stable order in which the two tasks were performed creates a clear limitation to the joint analyses of the two effects. Yet, the fact that cumulative interference can predict cumulative facilitation suggests a functional link between the two and points to a shared mechanism underlying both effects. As the classification tasks solely requires semantic processing, this mechanism and thus the origin of both effects seems to be located at the conceptual level.

Cumulative interference and facilitation are reflected by similar ERPs

The third key finding that suggests that cumulative interference and cumulative facilitation share the same underlying mechanism and thus both originate at the conceptual level are the very similar ERP components reflecting both effects. In picture naming, we found a posterior positivity starting around 250ms post picture onset, followed by a negativity in the same location starting around 450ms. In the classification task, the strong facilitation effect in the first classification cycle was reflected by a positive modulation starting 350 ms post picture onset at posterior electrode sites, followed by a posterior negativity starting around 450ms.

The posterior positivity in picture naming likely reflects processes linked to lexical retrieval. As the relative positivity increases with each newly named category member, it most likely reflects the increasing difficulty to select the targets' lexical entries for further production (e.g., Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017). Its onset is in line with ERP studies using other context effects to explore the time course of lexical retrieval (e.g., Aristei et al., 2011; Bürki, 2017; Christoffels et al., 2007; Lin et al., 2021; Maess et al., 2002; Piai et al., 2012; Strijkers et al., 2010) and also roughly corresponds to the onset of lexical selection estimated by meta-analyses (Indefrey, 2011; Indefrey & Levelt, 2004; for a critical discussion on these meta-analyses, see Strijkers & Costa, 2016). The posterior positivity observed in the classification task is interpreted as a reduced N400, reflecting conceptual-semantic processing. The onset, polarity and spatial distribution of the component is comparable to those reported in other semantic priming studies (semantic classification/judgement tasks: Geukes et al., 2013, McPherson & Holcomb, 1999; picture-naming: Blackford et al., 2012; Lorenz et al., 2021). In the context of cumulative facilitation, the positivity, which increases with each classified category member, most likely represents the increasing ease with which semantic information is accessed/integrated due to semantic priming induced by the preceding category members (e.g., Kutas & Federmeier, 2011).

These interpretations of the two positive modulations suggest two entirely different positive ERP components in the two tasks that reflect entirely different underlying processes. However, there is an alternative interpretation. There is also the possibility that the positivity found in the two tasks is (at least partly) the same component and thus reflects at least partly the same processes in both tasks. Lexical interference is necessarily conceptually mediated (Abdel Rahman & Melinger, 2011, 2019; Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010; Roelofs, 2018 and many others). Thus, the posterior positivity observed in the naming task might not be a purely lexical component but could also reflect conceptual-semantic processing. After all, many models of speech production assume bidirectional links between the conceptual and lexical level, thus allowing for parallel processing (Caramazza, 1997; Dell, 1986; Levelt et al., 1999). This has also recently been shown in an empirical study (Lin et al., 2022). Furthermore, similar early positive modulations in other speech production paradigms associated with related compared to unrelated contexts have also been interpreted to reflect semantic (priming) processes rather than lexical retrieval (e.g., Blackford et al., 2012; Janssen et al., 2015). Also, according to recent findings the same electrophysiological component can be linked to opposite behavioural effects (Rabovsky et al., 2021). The study found that the same posterior positivity in picture naming reflects both, a facilitatory effect of high semantic richness and an inhibitory effect of high feature density. Thus, cumulative (lexical-semantic) interference and cumulative (semantic) facilitation might both be reflected by a similar posterior positivity because they both involve conceptual-semantic processes and because conceptual and lexical processing likely overlap in time and (brain) space. The fact that the positive modulations in picture naming and semantic classification do not have an identical temporal dynamic (earlier onset and longer lasting component in picture naming) also fits with this interpretation. The earlier onset in picture naming is in line with empirical evidence suggesting that lexical-semantic processing is accelerated by the top-down intention to speak in tasks that require overt naming compared to tasks where no overt naming is necessary (Strijkers et al., 2012). The longer duration of the effect in picture naming is likely because it entails conceptual processing as well as lexical retrieval.

Apart from this posterior positivity, we also observed a negativity at posterior sites in both tasks between 450 and 600ms. The time course, topography, and polarity suggest that it is the same component in both experiments and the same component that has been reported by some previous continuous naming studies (Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017). It has been tentatively suggested that this component reflects the learning mechanism responsible for cumulative interference (Rose & Abdel Rahman, 2017), namely the strengthening of the connections between lexical concepts and their semantic features (Belke, 2013) or between conceptual and lexical representations (Howard et al., 2006; Oppenheim et al., 2010). As we found this late negative modulation to be part of the electrophysiological signature of both cumulative context effects, its function might indeed be related to the mechanism responsible for the accumulating effects. Our data could thus be taken as corroborating evidence for this interpretation, if we assume that cumulative interference and cumulative facilitation are both the result of the same learning mechanism (Belke, 2013). However, not all findings in the literature fit this interpretation. First, some studies investigating the electrophysiological signature of cumulative interference did not observe this modulation (Costa et al., 2009; Llorens et al., 2014). Second, one might have expected a positive instead of a negative modulation if the component indeed reflected the learning mechanism behind cumulative context effects. After all, studies investigating long- or short-lag repetition priming, with a presumably similar underlying mechanism (i.e., long-lasting changes to the production system), have predominantly linked repetition priming to positive modulations, not negative ones (e.g., Guillaume et al., 2009; Henson et al., 2004; Kiefer, 2005). Thus, while Study 2 revealed that the late posterior negativity cannot only be observed in picture naming but also in picture classification, further research is necessary to really understand the function of this component. Nonetheless, the similarity between the electrophysiological signatures of cumulative interference and cumulative facilitation strongly suggests a functional link between both effects.

Conclusion

Collectively, these three key findings point to a close relation of the two context effects and are best explained by models assuming a purely conceptual origin of cumulative semantic interference (Belke, 2013; Roelofs, 2018). Models assuming the origin of CSI at the interface between the conceptual and lexical level can, in their current state, not easily account for the results presented in this dissertation (Howard et al., 2006; Oppenheim et al., 2010). Their learning mechanisms responsible for cumulative effects is contingent on the activation of lexical information, which is not necessary in semantic classification. Thus, they cannot account for cumulative facilitation. However, there is the possibility that the lexical level is automatically activated during the classification task due to spreading activation from the conceptual to the lexical level (for empirical evidence against this assumption, see e.g., Catling & Johnston, 2006; Taikh et al., 2015). Under this assumption, a learning mechanism at the interface of the conceptual and lexical level might also explain cumulative facilitation, but only if lexical activation and not lexical selection suffices for the learning mechanism to kick in, as it is not likely that lexical selection occurs in a task that does not require overt speech production (for a similar explanation, see Belke, 2013; for empirical evidence along those lines, see Navarrete et al., 2021). Thus, one way forward in this discussion might be to test if, when and to exactly what extent the lexical level is involved in the classification task. For now, a purely conceptual-semantic origin of CSI is the most parsimonious explanation.

In the present dissertation, I did not set out to adjudicate between different models assuming a purely conceptual origin of CSI (Belke, 2013; Roelofs, 2018). Studies 1 and 2 focused on the location of the learning mechanism (i.e., the origin of the effect) but were not specifically designed to probe the actual learning mechanism behind cumulative interference (long-lasting learning mechanism (Belke, 2013) vs. temporary bias (Roelofs, 2018)). However, in Study 1 we observed that after several repetitions cumulative interference becomes weaker in long-lag trials (i.e., when there are many intervening items between category members). While this shows the influence of repetition on the CSI effect (which I discussed in great detail above), it also shows that CSI is not as persistent as previously assumed (Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010). This finding is in line with Schnur (2014), who also showed that cumulative interference disappears if category members are consistently separated by a large number of unrelated items (8 or more intervening items, Schnur, 2014). Study 1 thus provides corroborating evidence that the longevity of cumulative interference is limited. As explained in the introduction, based on this finding, Roelofs (2018) argues that the CSI effect cannot be the results of long-lasting changes to the production system (see e.g., Belke, 2013), as effects based on this kind of mechanism can still be observed after several weeks (e.g., repetition priming, see Mitchell & Brown, 1988). Instead, Roelofs argues for a more temporary bias towards the target after successful lexical selection, making it a strong competitor in the subsequent naming process of semantically related category members. The results observed in Study 1 provide tentative evidence in favour of this mechanism.

3.3 Cumulative interference as a tool to investigate the lexical representation of compounds

After Study 1 revealed that morphological complexity per se does not modulate the CSI effect, we used cumulative interference as a research tool in Study 3 to investigate the lemma representation of noun-noun compounds in speech production. Study 3 revealed that semantically related modifiers interfere with the production of the whole compound, which provides evidence that the compounds' constituent lemmas are activated during the production of the compound. Consequently, the results point to a complex lemma structure for noun-noun compounds, consisting of the holistic compound lemma and the lemmas of the compounds' constituents (Marelli et al., 2012). If they were represented in a single lemma like simple nouns (Levelt et al., 1999), we would not have expected interference in the compound condition, as the compounds themselves were not semantically related and should thus not have interfered with one another. While these results are in line with neuropsychological studies that tested participants with aphasia (e.g., Lorenz et al., 2014, 2022; Mondini et al., 2004; Semenza et al., 1997), they stand in contrast to most previous studies investigating compound processing in healthy adult speakers. These studies either found evidence for a single lemma representation (e.g., Lorenz, Mädebach, et al., 2018; Lorenz et al., 2021; Lüttmann et al., 2011) or only weak evidence for multiple lemmas in naming errors (Lorenz, Regel, et al., 2018). These different results are most likely the result of the different experimental paradigms that were used. As explained in the introduction, it is likely that modifier-related effects in healthy adult speakers are too small to be detected in some picture naming paradigms, such as the PWI or the determiner-priming paradigm, due to concomitant conceptual facilitation obliterating the small interference effect (e.g., Abdel Rahman & Melinger, 2019; Lin et al., 2022; Rose & Abdel Rahman, 2016). In contrast, the continuous picture naming paradigm used in Study 3 is more sensitive to detect interference because it reveals long-lasting interference that accumulates within categories in the context of short-lived, non-increasing conceptual priming. Therefore, even weak interference can be observed because it is not cancelled out by concomitant facilitation (e.g., Abdel Rahman & Melinger, 2019; Lin et al., 2021; Rose & Abdel Rahman, 2016).

Surprisingly, however, a recently published determiner-priming study also provides corroborating evidence for a multiple-lemma representation of compounds in healthy adult speakers

(Lorenz et al., 2022). They investigated the lemma representation of compounds in participants with aphasia and tested a group of healthy adult speakers matched in age and educational background as a control group. In their picture naming task, Lorenz et al. (2022) used gender-marked determiners as primes and noun-noun compounds as targets and found that compound production in the healthy speakers (but also in a subgroup of the PWA) was facilitated by both, head-congruent as well as modifier-congruent determiners. As this suggests that the syntactic information of the modifier was activated during compound production, the results support the multiple-lemma account (Marelli et al., 2012). Thus, the results are in line with those presented in the present dissertation. Meanwhile, they raise the question why the presumably small modifier effect could be detected in this recent study (Lorenz et al., 2022) but not in an earlier one, which used the same material and the same paradigm (Lorenz, Mädebach, et al., 2018)? First of all, it is important to mention that the modifier effect reported by Lorenz et al. (Lorenz et al., 2022) disappeared when the authors changed the statistical analysis (ANOVA instead of linear-mixed models). This suggests a rather weak effect, which provides corroborating evidence for our assumption that modifier effects are in general rather weak and not easily detected. Nonetheless, one possible reason that a weak effect was found by Lorenz et al. (2022) but not by Lorenz, Mädebach, et al. (2018) might have been that the modifier effect was slightly larger in the former than the latter study because of age-related effects. Participants in the former study were significantly older than in the latter one (53 years vs. 22 years), which might have either increased the priming effect (e.g., attention control, Piai et al., 2013) or somehow affected the processing of the compound targets (for a more detailed discussion, see Lorenz et al., 2022). Importantly, however, the latter explanation does not necessarily imply a different representational format of compounds in older than in younger speakers. In fact, preliminary results of a study we recently conducted with a group of older participants (mean age: 70 years; Döring et al., n.d.) does not suggest that the representational format of compounds changes with age, as a function of learning and exposure (for contradicting data from comprehension, see Duñabeitia et al., 2009; Reifegerste et al., 2017). In the continuous picture naming task, we found evidence for activated constituent lemmas during compound production in the elderly speakers, just as for the younger speakers. Consequently, our preliminary data suggests that the multiple-lemma representation of compounds in speech production is stable across the lifespan (Döring et al., n.d.).

To summarise, Study 3 in the present dissertation provided evidence that compounds are represented in a complex representational format on the lemma level, with constituent lemmas accompanying the holistic compound lemma (Marelli et al., 2012). This finding was corroborated by a recent study (Lorenz et al., 2022) and preliminary data of a recently conducted study suggest that the lemma representation of compounds does not change with age (Döring et al., n.d.). Importantly, these results show that word morphology plays an important role at the lexical-syntactic level. This advances our understanding of the speech production system and requires models of speech production to be adapted accordingly (e.g., Levelt et al., 1999).

Yet, even more research is needed to fully understand how the representation of compounds at the lemma level is influenced by semantic transparency. Study 3 provides tentative evidence that constituent lemmas of opaque compounds are not activated during compound production, which points to a single, holistic lemma representation for those compounds (see also Lorenz & Zwitserlood, 2016). This would suggest that the semantic transparency status of a compound determines its lemma structure. However, Study 3 was not explicitly designed to distinguish between the representation of transparent and opaque compounds. Semantic transparency was solely included as a covariate to control for variability in the items. On a continuum, the majority of our compounds were more transparent than opaque (about 70%, heads as well as modifiers), which might have influenced the results. Thus, it is necessary to conduct further continuous picture naming studies which are explicitly designed to investigate the representation of fully transparent (transparent modifier & transparent head), semi-transparent (transparent modifier & opaque head or opaque modifier & transparent head) and fully opaque compounds (opaque modifier & opaque head) to get a comprehensive understanding of the lemma representation of all types of compounds. When testing for transparency effects, it would also be desirable to investigate if the results are modulated by the way semantic transparency is defined and quantified. While we defined transparency as the extent to which the meaning of the constituents is maintained in the meaning of the compound, others define it in terms of compositionality. In that case, a compound is assumed to be transparent when its meaning is easily predictable from the meaning of its constituents (e.g., Günther & Marelli, 2019). As these differences might influence the outcome, it would be important to know to which extent and in what way.

4. Conclusion

This dissertation contributes to a better understanding of several aspects of speech production. First, it provides a more comprehensive understanding of cumulative semantic interference, a semantic context effect which is extensively used to investigate lexical-semantic processing. The results reported in Study 1 and 2 suggest that cumulative interference 1. originates at the conceptual level (Belke, 2013; Roelofs, 2018), 2. is not modulated by morphological complexity and 3. is influenced by repetition. These findings allow researchers to make more informed predictions when using cumulative interference as a research tool in the future. Secondly, this dissertation advances the discussion on the lemma representation of compounds in speech production by being the first to use the cumulative interference effect to investigate this research topic. Study 3 provides evidence that the compounds' constituent lemmas are activated when healthy adult speakers produce a compound, which points to a multiple-lemma representation of compounds (Marelli et al., 2012). This implies that morphological complexity can affect the representational format at the lemma level during speech production. This dissertation thus not only advances our understanding of compound processing in speech production but also extends our knowledge about the architecture of our language production system.

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RESEARCH ARTICLE

Cumulative semantic interference is blind to morphological complexity and originates at the conceptual level

Anna-Lisa Döring[1]*, **Rasha Abdel Rahman**[1], **Pienie Zwitserlood**[2], **Antje Lorenz**[1]

1 Department of Neurocognitive Psychology, Humboldt-Universität zu Berlin, Berlin, Germany,
2 Department of Psychology and Otto Creutzfeldt Center for Cognitive and Behavioral Neuroscience, Westfälische Wilhelms-Universität Münster, Münster, Germany

* anna-lisa.doering@hu-berlin.de

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Abstract

When naming a sequence of pictures of the same semantic category (e.g., *furniture*), response latencies systematically increase with each named category member. This cumulative semantic interference effect has become a popular tool to investigate the cognitive architecture of language production. However, not all processes underlying the effect itself are fully understood, including the question where the effect originates from. While some researchers assume the interface of the conceptual and lexical level as its origin, others suggest the conceptual-semantic level. The latter assumption follows from the observation that cumulative effects, namely cumulative facilitation, can also be observed in purely conceptual-semantic tasks. Another unanswered question is whether cumulative interference is affected by the morphological complexity of the experimental targets. In two experiments with the same participants and the same material, we investigated both of these issues. Experiment 1, a continuous picture naming task, investigated whether morphologically complex nouns (e.g., *kitchen table*) elicit identical levels of cumulative interference to morphologically simple nouns (e.g., *table*). Our results show this to be the case, indicating that cumulative interference is unaffected by lexical information such as morphological complexity. In Experiment 2, participants classified the same target objects as either man-made or natural. As expected, we observed cumulative facilitation. A separate analysis showed that this facilitation effect can be predicted by the individuals' effect sizes of cumulative interference, suggesting a strong functional link between the two effects. Our results thus point to a conceptual-semantic origin of cumulative semantic interference.

Introduction

At the heart of effective language production is the lexical selection process, namely the selection of the lexical representation that best expresses the meaning of the preverbal, conceptual message. This process has been intensively investigated, mostly by picture naming studies that systematically manipulated the semantic context within which a target picture appeared. This

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manipulation is based on the following two assumptions that are shared among most researchers in the field: 1. lexical access in speech production is semantically driven, meaning that a speaker must first activate the semantic representation of the to-be-named target (at least to a minimal degree) before lexical access is initiated, and 2. semantically related lexical entries are initially co-activated via spreading activation at the conceptual level [e.g., 1] before the target entry is selected from among the co-activated items at the lexical level [e.g., 2–10]. Regarding the latter, it is assumed that the level of co-activation on the conceptual level is directly modulated by the degree to which the concepts are related to the target concept, with stronger co-activation for closely related concepts.

Different naming paradigms have been used to investigate lexical-semantic encoding, starting with the picture-word interference (PWI) paradigm [11–14, see 15 for a recent overview], followed by the blocked-cyclic naming task [e.g., 16–20]. More recently, the continuous picture naming paradigm with its robust cumulative semantic interference (CSI) effect has become increasingly popular [21, 22]. It has been used to investigate lexical access in bilinguals [23], semantic integration of newly acquired words [24], lexical access in a social settings [25, 26], the lexical representation of compounds [27] or whether or not lexical selection is a competitive process [e.g., 22, 28, 29]. Despite this multitude of studies using CSI as a tool to investigate different research questions, not all underlying processes of the effect itself are fully understood. It is, for example, still a matter of debate where CSI originates [e.g., 3, 9, 22, 29, 30]. It is also still unknown if and how CSI effect is affected by lexical variables such as the morphological structure of the stimuli used in the naming task. The current study aims to address both of these issues.

The origin of cumulative semantic interference

In the continuous picture naming paradigm, members of different semantic categories (e.g., *desk*, *chair*, *shelf*, *bed*, *wardrobe* for the category *furniture*) are presented for naming in a seemingly random order, separated by 2 to 8 unrelated objects [filler items or members of other categories; e.g., [22]). Participants' naming latencies within each semantic category systematically increase in a linear fashion with each ordinal position, that is, as a function of previously named objects of the same category. This CSI effect is independent of the number of intervening unrelated items [22, 28, 30–32; but see 33] and survives multiple repetition cycles [27, 28, 34]. All existing models agree that the locus of cumulative interference, that is, the level at which it comes into effect and behavioural consequences arise, is the lexical level [3, 9, 22, 28–30]. Here, CSI is interpreted in terms of increasing difficulty to select a target's lexical representation—from now on called "lemma" [6]—amongst a group of co-activated lemma representations. However, activation within the lexical system is short-lived [e.g., PWI paradigm; [12] and thus not suitable to explain the longevity and accumulating nature of CSI. Therefore, different learning mechanism have been proposed, where structural changes to the system are responsible for the persistence of the effect. The level at which these occur, meaning the level at which cumulative interference actually has its origin (as opposed to its locus, mentioned above), is still a matter of debate.

Howard and colleagues [22] and Oppenheim and colleagues [29] both locate the origin at the interface of the conceptual and lexical level, but differ with respect to the underlying learning mechanism. Howard et al. assume that producing a word strengthens the connection between the concept and its lemma entry, thus priming its future activation. A subsequently presented picture of a member from the same category activates semantically related concepts via spreading activation [1,4–7, 9, 10], including the previously named category member. Due to the now strengthened connection between the concept and lemma, its lemma is more strongly activated than previously unnamed objects, making it a strong competitor in the lexical selection process of the to-be-named object. As each additional category member adds to the cohort of competing lexical items, the number of strong competitors systematically increases, resulting in accumulating interference [22]. While Oppenheim and colleagues [29] also localise the origin of the CSI effect at the conceptual-lexical interface, they explain cumulative interference without competitive lexical selection. in their view, incremental learning not only entails the reinforcement of connections between the conceptual and lexical entry of the named target but also the weakening of connections between concepts and lexical representations of co-activated non-targets. By means of computational modelling, Oppenheim et al., [29] showed that this error-driven learning suffices to explain the accumulation of interference without assuming a competitive lexical selection process [see also 28].

In contrast to these accounts, others argue for a purely conceptual origin of cumulative interference [9, 30]. Belke [30] proposes a learning mechanism at the conceptual level, where the links between a target's lexical concept (a unitary conceptual representation node) and its semantic features are strengthened after the target's lexical concept has been selected [30; for a model of lexical-semantic memory of this kind, see, e.g., 35]. When subsequently trying to name a semantic relative, these strengthened links will result in strong co-activation of the lexical concept named earlier and its lemma, causing competition during lexical selection of the to-be-named relative. The rationale is identical to that of Howard et al. [22] in that each additionally named member of a category will increase the competition during lexical selection, resulting in accumulating interference. Belke supports her claim about the conceptual origin by demonstrating that cumulative context effects can also be observed in purely semantic tasks that do not (necessarily) involve the lexical level. When participants classified, via button-press, objects of different semantic categories as either man-made or natural, cumulative facilitation was observed instead of interference: participants' response latencies systematically decreased within semantic categories. Belke assumes that the repeated activation of semantic features related to either man-made or natural entities of a certain semantic category induces accumulating activation at the conceptual level, rendering the man-made or natural distinction within these semantic categories increasingly easier. As the locus of the effect is identical to its origin, namely the conceptual level, facilitation instead of interference is observed. In addition, Belke reports that semantic facilitation and interference influence one another in an experiment including both tasks, picture naming and semantic classification [30, Exp. 5]. As the classification task only requires conceptual processing, Belke argues for a common conceptual origin of the two effects. While this learning mechanism had not been computationally implemented, Roelofs [9] provided a computational simulation of a similar account. Here, the learning mechanism at the conceptual level was implemented by means of a temporary bias, which not only successfully simulated cumulative interference in naming but also the cumulative facilitation reported by Belke [30].

The models assuming the origin of cumulative interference at the lexical-semantic interface were designed to accommodate speech production data, and thus do not provide explicit explanation for cumulative facilitation found in semantic classification [22, 29]. However, if we assume that the classification task does not entail activation of lexical information, a learning mechanism at the interface between the conceptual and lexical level would not seem to be able to explain cumulative facilitation observed in the classification task. Thus, further studying cumulative facilitation seems a good way forward when investigating the origin of cumulative context effects in speaking. The first aim of the current study is therefore to get more comprehensive understanding of cumulative facilitation and its similarities and difference to cumulative interference.

Cumulative semantic interference and morphological complexity

To make informed predictions when using cumulative interference as a tool to test theories of the cognitive architecture in language production, it is also essential to identify the conditions under which it arises, and which factors modulate the effect. While plenty of studies have systematically explored the influence of different distractor-target types on semantic context effects in the PWI paradigm [7, 36–45], much less is known about their influence on cumulative interference in the continuous paradigm. Thus far, studies have shown that cumulative interference can be observed for targets that are only associatively but not categorically related [45] and that more closely related category members induced greater cumulative interference than more distant ones [34]. However, while many continuous naming studies included a mixture of simple nouns, such as *table* or *shelf*, and morphologically complex noun-noun compounds, like *woodworm* and *bookshelf* [22, 25, 30, 31, 34, 45], it is still unclear whether morphologically complex compounds induce identical CSI to their morphologically simple noun counterparts.

Given that cumulative interference is clearly semantically driven, one could argue that morphology is unlikely to be relevant at all. However, interference is assumed to come into effect at the lexical level, more specifically at the lemma level [e.g., 6, but see 4], and recent empirical evidence suggests that compounds and simple nouns may not be represented in the same way at this level. While simple nouns (e.g., *shelf*) are assumed to have a single entry at the lemma level [6], studies on compounds (e.g., *bookshelf*) suggest that they may have multiple lemma representations [27, 46, 47], namely morpheme-sized lemma entries (*book* and *shelf)* that complement the holistic compound lemma [for evidence from neuropsychological studies, see e.g., 46, 48, 49]. If compounds and simple nouns are differently represented on the level where cumulative interference is said to come into effect, different activation patterns might lead to different patterns of cumulative interference [for contrasting evidence, see e.g., 43, 50].

While PWI studies report identical interference for compound distractor-target pairs (wooden spoon—bread knife; original materials in German) and simple noun distractor-target pairs [spoon—knife; 43, Exp. 2], research suggests that effects in PWI are not necessarily transferable to the continuous paradigm [for recent discussions, see e.g., 3, 27]. The only study that systematically manipulated morphological complexity in a continuous picture naming paradigm is our recently published study that investigated the representation of German compounds in speech production [27]. In this study, participants named pictures in a compound and a simple noun condition. Category membership of compound targets was established through the compounds‘first constituents (category animals: ***dog*** *lead*, ***zebra*** *crossing*, ***pony*** *tail*, ***mouse*** *trap*, ***cat*** *litter*), while the compounds themselves were not semantically related. The simple noun, control condition consisted of pictures depicting the compounds' first constituents (*dog*, *zebra*, *pony*, *mouse*, *cat*). We observed cumulative interference in the simple noun as well as the compound condition, indicating that the semantic relationship between the compounds' first constituents influenced compound production. As this suggests activation of constituent lemmas during compound production, the results support the multiple-lemma representation account of compounds [46]. Importantly, we observed significantly weaker interference for compounds than simple nouns. While one could take this as evidence for the influence of morphological complexity on CSI, it is important to remember that the interference in the compound condition was only induced by the compounds' first constituents [27]. In German, a compound's grammatical features are determined by its second constituent (i.e., its head), which also carries the bulk of the meaning of a semantically transparent compound (e.g., Zahnbürste [toothbrush]), while the second constituent, the modifier, merely provides further specification [i.e., a toothbrush is a type of brush, used for teeth; cf. 51, 52].

Consequently, any effects solely related to the modifier constituents of compound targets are likely to be weaker than those related to either the head, or the compound as a whole [see 27]. Thus, from these results we cannot infer whether semantically related compounds (*bookshelf*, *canopy bed*, *arm chair*) induce identical levels of CSI to their semantically related simple noun counterparts (*shelf*, *bed*, *chair*). The current study aims to answer this question.

The current study

The overall purpose of this study is to gain a more comprehensive understanding of the cumulative semantic interference effect found in the continuous picture naming paradigm. We conducted two experiments with the same group of participants and the same visual stimuli.

Experiment 1 used a continuous picture naming task designed to investigate whether the CSI effect differs for morphologically complex noun-noun compounds (*bookshelf*, *kitchen table*) and their corresponding morphologically simple head nouns (*shelf*, *table*). The picture stimuli, belonging to different semantic categories (e.g., furniture, animals, clothing. . .), were selected in such a way that they could equally well be named with either a simple noun or a compound noun (e.g, *shelf* vs. *bookshelf*). In a familiarisation phase, half of the participants learned that 50% of the pictures correspond to compound names (*bookshelf*) and 50% to simple noun names (*cup)*, while the other half of the participants learned it the other way around (*shelf* and *tea cup*). Based on previous studies [22, 30], we expected to find robust cumulative semantic interference in the simple noun condition, reflected by a linear increase in naming latencies with each ordinal position, as a function of previously named pictures from the same semantic category. For the compound condition we also expected cumulative interference. However, we predicted that interference might be weaker for compounds than simple nouns as multiple lemmas (and concepts) become activated [*bookshelf*, *book*, and *shelf*, e.g., 27; but see 43]. This might lead to overall weaker activation levels, as some activation might dissipate across the semantic network via the activated concept of the compound's first constituent (*book*). As the first constituent was not part of the same semantic category as the compound itself (i.e., furniture), its reciprocal activation (from lemma to concept) would co-activate other members of its semantic category (i.e., journal, magazine . . .), which could result in weaker accumulating interference within the category of the compound. In case of an observed difference in interference between the two word types, we wanted to ascertain that this would not be due to differences in semantic similarity between category members in the simple noun or the compound condition. Thus, we included a measure for semantic similarity into the analysis to control for this semantic factor.

Experiment 2 employed a semantic classification task, in which the same participants saw the picture stimuli from Experiment 1 in the exact same order and were instructed to classify the depicted objects as either man-made or natural (via button-press). The aim of this experiment was twofold. First, we wanted to replicate cumulative facilitation which, thus far, has only been reported once in a manual task [30] and once in a verbal classification task [53]. At the same time, we wanted to gain a better understanding of cumulative facilitation by investigating whether it survives multiple repetitions and whether it is modulated by semantic similarity. This would provide a more comprehensive profile of cumulative facilitation concerning its commonalities and differences to cumulative interference.

Second, we wanted to investigate whether one semantic context effect can be used to predict the other, which would point towards a causal link between the two effects and thus corroborate a conceptual origin of cumulative semantic interference in the picture naming task [30]. As the classification task always followed the naming task, we used the interference effect found in Exp 1 to predict the facilitation effect in Exp 2.

We included Word type as a predictor in the analysis of the classification task to control for the possibility that participants activated different lexical concepts / a different set of conceptual features upon seeing the pictures as a result of previous naming them with different labels (e.g., either as *kitchen table* or *table*; note that each participant named half of the targets with a simple word, the other half with a compound). However, even if this were the case, we expected identical levels of facilitation, independent of previous simple-word and compound naming. The task requires participants to activate nodes identifying the object as either man-made or natural, which should be identical for lexical concepts such as *KITCHEN TABLE* and *TABLE*. As activation levels should also be comparable for both concepts with regards to man-made or natural nodes, we expected similar facilitation for both previously used word types.

Experiment 1

Material and methods

Participants. Thirty-six native speakers of German (20 female, 16 male) between the age of 18 and 35 (mean 26.7 years) were included in the analysis. Due to technical problems, three participants had to be excluded and replaced. The sample size was chosen following a power analysis [simr package, 54]. Based on a previous experiment using linear mixed-effects models to analyse log-transformed reaction times from a continuous picture naming study with simple-noun targets [25], we predicted an effect size (*b)* of about 0.04 for the interference effect in the simple noun (control) condition for five presentations (naming cycles 1–5). To account for the possibility of a smaller interference effect in the compound condition, we used a *b* of 0.025 when simulating the outcome of the anticipated model with 1000 iterations for the compound condition. With 36 participants we reached a power estimate of 84,6% (95% confidence interval: 82.2, 86.8) for detecting the hypothesized cumulative semantic interference in the compound condition. All participants had normal or corrected-to-normal vision and received monetary compensation or course credit for their participation. The study was approved by the local ethics committee of Humboldt-Universität zu Berlin via written consent and is in accordance with the Declaration of Helsinki. All subjects gave informed written consent.

Materials. The stimuli set consisted of 140 coloured photographs of 70 man-made and 70 natural entities and their written names. The set included 90 targets, 30 filler items and 20 practice items. The targets belonged to 18 different semantic categories (e.g., clothes), with five members each. Care was taken that each photograph could be named with a simple noun (e.g., *Bluse* (blouse)) or a noun-noun compound (e.g., *Seidenbluse* (silk blouse)). To verify the suitability of our stimuli set, two pre-studies were conducted. In the first online survey, we established a measure for picture/label-fit, to control for possible differences between the two word types. Forty native speakers of German (mean age: 26.9 years; range: 18–47) took part in the survey (20 participants per picture-label pair). The participants were presented with a picture and the corresponding label in either the compound (*silk blouse*) or the simple noun (*blouse*) condition and were asked to use a six-point Likert scale (6 = perfectly/entirely; 1 = not at all) to indicate how well the label describes the picture. The results showed that the compound labels (mean rating: 5.34, $SD = 1.0$) and the corresponding simple noun labels (mean rating: 5.36, $SD = 1.0$) described the pictures equally well ($t = 0.30$, $p = 0.77$). As prior research suggests that within-category semantic similarity modulates cumulative interference [34], we conducted a second online survey to establish a measure of semantic similarity for the statistical analysis. Eighty native speakers of German (mean age: 33.5 years; range: 18–70) took part in the survey (20 participants per item pair). The participants were presented with word pairs (i.e., two members of a category) and were asked to use a six-point Likert scale (6 = very closely related; 1 = not at all related) to indicate the semantic similarity of the two items. Semantically similar items were defined as sharing many semantic features (e.g., *apricot* and *plum*: both are fruits, can be eaten, grown on trees, have a stone, are round . . .), while items with few or no shared features were defined as semantically distant (e.g., *apricot* and *telephone*). For each material set, participants either rated two compounds (e.g., *silk blouse* and *winter coat*) or the corresponding simple nouns (e.g., *blouse* and *coat*). The results showed that the members of the 18 categories were overall perceived as closely related (mean rating overall: 4.5, *SD*:1.2). This was confirmed for both word types, but additional analyses showed that simple nouns were perceived as significantly more closely related (mean: 4.64, *SD*: 1.31, range: 3.3–5.5) than compounds (mean: 4.40, *SD*: 1.35, range: 3.0–5.1, $t = 10.67$, $p < 0.001$).

The 50 filler and practice items were semantically unrelated to the targets and care was taken to ensure that there were no morphological overlaps, meaning that no constituent appeared more than once in the stimuli set. Due to an oversight, the constituent *Hammer* (hammer) was included twice, once as the first constituent in the compound *Hammerhai* (hammerhead (shark)) and once as the second constituent in *Gummihammer* (rubber hammer). All photographs were scaled to 3.5cm x 3.5cm and had a homogenous light grey background. Appendix A lists all materials used in this experiment.

Apparatus. Participants were seated in a noise-cancelling booth, approx. 80 cm from the screen and approx. 30 cm from the microphone. The pictures were presented on a 19” inch screen (1280x1024), using version 17.0 01.14.14 of the software Presentation® (Neurobehavioural Systems, Inc, www.neurobs.com) and response times were registered by a voice-key (self-made) and a Sennheiser MKH 416 P48 microphone.

Experimental design. Eighteen different lists were created on the basis of a master list that contained 90 slots for the target words and 30 slots for the filler items. The five slots for the five members of a category were separated by 2, 4, 6 or 8 intervening items [lag value; e.g., 22]. The order in which categories appeared within a list and the order of the five members within each category were unique for each list. Care was taken to keep semantically related categories apart (e.g., land animals, marine animals, and insects) to avoid participants creating superordinate categories.

The two word types (compounds, simple nouns) were presented block-wise, thus every list was split into two blocks, each containing 45 critical and 15 filler items in the compound or simple noun condition. To directly compare the processing of compounds and simple nouns, two versions of each of the 18 lists were created and presented to different participants. In version one, participants were asked to use simple nouns when naming the pictures of the first block (e.g., *Ring* (ring)) and compounds when naming the pictures of the second block (e.g., *Orangensaft* (orange juice)). In version two, participants were asked to use compounds for the first block (e.g., *Ehering* (wedding ring)) and simple nouns for the second (e.g., *Saft* (juice)). This counterbalanced order ensured that each participant saw each picture in only one word type condition. Note that participants were not explicitly informed about the two word types, and simply learned the picture labels during the familiarisation phase. Every participant was presented with five differently randomised versions of their list to enhance statistical power and to further investigate the effect of repetition on the cumulative semantic interference effect. This factor will be called *Presentation*. To ensure that participants did not have to switch between the two word type conditions, we used a blocked design.

Procedure. Prior to each word type condition (compounds, simple nouns), there was a familiarisation phase. Participants were presented with the 70 pictures and corresponding labels of the upcoming word type condition (45 targets, 15 filler items, 10 practice items) in a random order on the screen (one picture at a time) and were asked to remember the correct label. They moved on to the next picture by themselves and thus had as much time as needed during the familiarisation phase. In the main experimental session, a fixation cross was shown for 500 ms at the start of each trial, followed by the picture. The picture was presented until a response was initiated or for a maximum of 2500 ms. After an inter-trial interval of 2 seconds, the next trial started. Participants were instructed to name the pictures as fast and as accurately as possible, using the label they had seen during the familiarisation phase. Naming latencies were recorded with the help of a voice-key from picture onset and the experimenter coded any voice-key or naming errors (incorrect responses, stuttering etc.).

Analysis

The data analysis was done with R [55]. Naming latencies were analysed for target trials only. Trials in which pictures were named incorrectly or dysfluently (3.5%), in which the voice-key was triggered too late (0.9%) or in which other technical or experimenter errors occurred (1.6%) were excluded from the analysis. For the identification of outliers, we combined light a-priori screening for artefactual responses with a removal of outliers that were not within normal distribution of the final model's residuals [for more details on the procedure, see 56]. The a-priori screening resulted in an exclusion of 1.3% of the data (RT < 300 ms), while a further 2.55% were excluded after model fitting (standardised residuals > than 2.5).

The inverse-transformed reaction times were fitted with a series of linear mixed effect models [LMM; 57], using the function lmer of the R package lme4 [58] and *p*-values were computed with the lmerTest package [59]. As the reaction time data were not normally distributed, we used the Box—Cox procedure [60] implemented in the boxcox-function in the package MASS [61] to identify the most appropriate transformation. However, untransformed RTs yielded similar results. Model comparisons were performed to identify the best fitting model. Starting with a maximal model, the model was first simplified by successively removing those random effects that explained the least variance, aiming to include the maximal random effect structure which enables model convergence and does not lead to overfitting [using the rePCA function; see 62]. The fixed effect structure was then reduced by successively excluding covariates and/or interaction terms, and then compared until the simpler model explained the data significantly worse than the more complex one (significant $\chi 2$ test in the anova function). The fixed structure of the initial model also included the covariates Lemma frequency and Word length. Neither of them improved model fit and were thus excluded from the analysis.

The final model used for the main analysis included main fixed effects and a three-way interaction of the predictors Word type (compound vs. simple noun), Ordinal position (five ordinal positions of members within one category) and Presentation (Presentations 1–5, i.e., first naming cycle and four repetitions with different lists) and main fixed effects and a three-way interaction of Word type, Ordinal position and Semantic similarity (for each item: mean values from semantic similarity rating). Picture fit (for each item: mean values from picture/label-fit rating) and Trial (consecutive trial number) were included as covariates. The latter was included to account for changes in the course of the experiment [i.e., trial-by-trial sequential effects, e.g., 53, 56, 63]. The random structure included random intercepts for Subjects, semantic categories and items nested within categories, random slopes for Word type for each participant, as well as random slopes for Presentation, Ordinal position, Picture fit, Semantic similarity and the interaction of Word type and Presentation for each participant (omitting correlations to facilitate convergence). The predictor Word type was contrast-coded using effect coding, while the predictor Ordinal position was contrast-coded using polynomial contrasts. Polynomial contrasts test for a linear trend in the data (among others), that is, whether the increase in response times from ordinal position 1 to 5 is linear or not. The cubic and quadratic trends were excluded from the analysis as they did not improve model fit [for more details on contrast-coding, see 64]. The two predictors Presentation, Semantic similarity and the covariates Picture fit and Trial were centred and entered as continuous variables.

In a second analysis we included the factor Lag (number of intervening items between the category members on Ordinal position 1–5) as an additional predictor in the above-mentioned model to investigate its influence on cumulative interference. Here, only data from ordinal position 2–5 were considered because there is no lag before ordinal position 1 [e.g., 18, 26, 29]. The factor Lag was centred and then added to the above model as a fixed effect in a three-way interaction with Ordinal position and Presentation.

Results

Table 1 contains the results of the main LMM analysis. As expected, naming latencies were significantly longer for compounds (Ø = 863.0 ms) than for simple nouns (Ø = 752.1 ms; main effect: word type). Furthermore, Picture fit significantly influenced overall naming latencies (main effect: Picture fit), with shorter naming latencies for items with higher picture-fit ratings. Crucially, the data shows a significant main effect of Ordinal position, reflecting the linear increase of naming latencies from one ordinal position to the next

Table 1. Main model Experiment 1. 1000/RT ~ Word type*Ordinal position *Presentation + Word type*Ordinal position*Semantic similarity + Picture fit+ Trial + (Word type*Presentation+ Ordinal position +Picture fit+ Semantic similarity||Subject) + (1|Category \ Item).

Predictors	**-1000/RT**			
	Estimates	*std. Error*	*t-value*	*p*
(Intercept)	-1.35	0.029	-46.73	**<0.001**
Word type	0.21	0.031	6.87	**<0.001**
Ordinal position	0.09	0.008	11.61	**<0.001**
Presentation	-0.07	0.004	-16.52	**<0.001**
Semantic similarity	0.08	0.021	3.65	**<0.001**
Picture fit	-0.11	0.020	-5.33	**<0.001**
Trial	<0.001	<0.001	3.14	**0.003**
Word type * Ordinal position	-0.02	0.010	-1.54	0.123
Word type * Presentation	-0.02	0.005	-3.32	**0.002**
Ordinal position * Presentation	< -0.01	0.003	-0.64	0.520
Word type * Semantic similarity	-0.04	0.040	-1.05	0.290
Ordinal position: Semantic similarity	0.02	0.010	2.07	**0.039**
Word type * Ordinal position* Presentation	-0.01	0.007	-0.92	0.355
Word type *Ordinal position * Semantic similarity	0.02	0.020	1.17	0.241

Random Effects

	Variance	**Sd**
Subjects (Intercept)	0.02	0.16
Subjects (Word type)	0.01	0.10
Subjects (Presentation)	< 0.01	0.02
Subjects(Ordinal Position)	< 0.01	0.04
Subjects (Picture fit)	< 0.01	0.04
Subjects(Semantic similarity)	< 0.01	0.04
Subjects (Word type * Presentation)	< 0.01	0.03
Item (Intercept)	0.002	0.05
Category \Item (Intercept)	<0.02	0.13
Residuals	0.07	0.26

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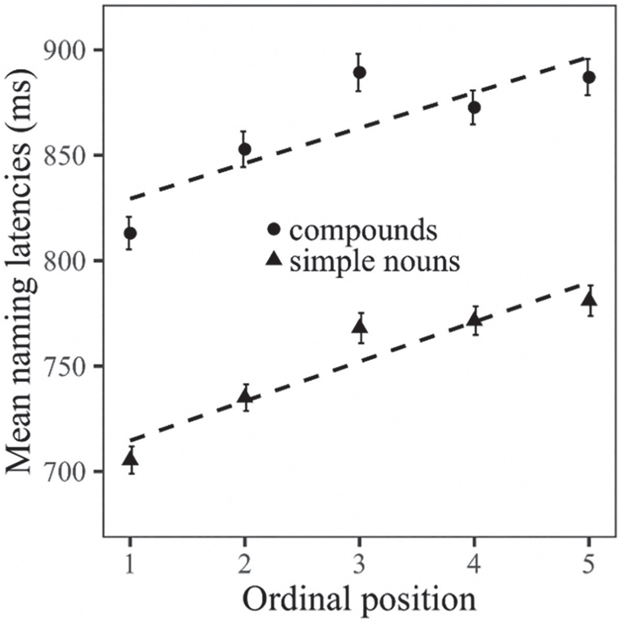

Fig 1. Mean reaction times (naming latency) and standard error (in milliseconds) observed in Experiment 1 broken down by ordinal position and word type.

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within semantic categories. Importantly, however, the factors Ordinal position and Word type did not interact, indicating that the magnitude of the cumulative semantic interference effect (i.e., the slope of the linear increase) was identical in both word type conditions (average increase per ordinal position: compounds = 18.5 ms; simple nouns = 19.0 ms, see Fig 1). Overall, naming latencies increased throughout the experiment (main effect Trial) but decreased with each repetition (main effect Presentation), an effect that differed between the word types (interaction Word type*Presentation). A post-hoc analysis using a nested version of the same model showed that the factor Presentation had a greater influence on compound (t = -15.84, $p < 0.001$) than on simple noun targets (t = -12.42, $p < 0.001$). However, there was no significant interaction between Ordinal position and Presentation and no interaction between Word type, Ordinal position and Presentation, suggesting that the cumulative semantic interference effect was present for both word types in all five naming cycles. We also found a significant interaction between Ordinal position and Semantic similarity, an effect that did not differ between word type conditions (interaction Word type*Ordinal position*Semantic similarity). As illustrated in Fig 2, the closer the items of one category are related (high semantic similarity), the larger the observed interference effect (difference in naming latencies between the first and last member of each category).

The results of the second analysis including Lag as an additional predictor mirror those of the main model, so we only report the results concerning the new predictor. There was no main effect for Lag (t = 0.86, p = 0.39) and only a trend for the interaction between Lag and

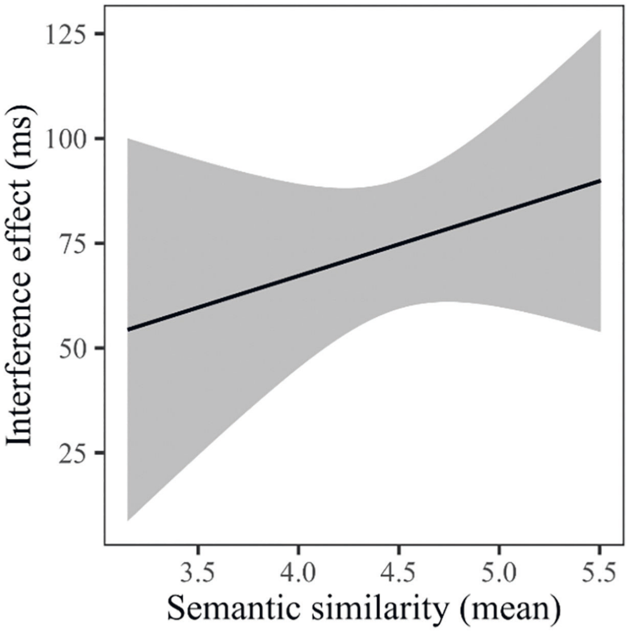

Fig 2. Visual illustration of the interaction between the interference effect (difference between mean naming latencies on ordinal position 1 and 5 (in ms)) and the semantic similarity rating score.

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Ordinal position (t = -1.84, p = 0.07). However, the three-way interaction between Lag, Ordinal position and Presentation was significant (t = -2.59, p = 0.01), suggesting that the influence of Lag on the interference effect differed between repetitions. This was confirmed by separate post-hoc analyses of each of the five presentations. While the interference effect was independent of lags in presentations 1–4 (all $p > 0.1$), it was significantly influenced by Lag in presentation 5, with shorter lags inducing stronger interference than longer lags (see S2 Appendix for a visual illustration of the predicted effect). However, when collapsed over all presentations, all four levels of the factor Lag (i.e., 2,4,6,8) induced significant cumulative interference when analysed separately (Lag 2: t = 3.71, $p < 0.001$; Lag 4: t = 4.13, $p < 0.001$; Lag 6: t = 2.76, $p < 0.01$; Lag 8: t = 2.62, p = 0.01).

Discussion

In Experiment 1, we observed the expected cumulative semantic interference effect [22] and found that the magnitude of the interference effect was modulated by the semantic similarity between category members. More closely related items caused greater interference, corroborating results from other continuous naming studies [34]. With regard to word type, participants took significantly longer to produce compounds than simple nouns. This expected finding can either be attributed to word-type inherent differences, such as word length and frequency, or to the fact that all compounds were subordinate-level words, which often induce longer naming latencies than basic-level simple nouns [44, 65–67]. Our key finding, however, concerns the identical slopes of increase in naming latencies from one ordinal position to the next, for both word types. This demonstrates that cumulative semantic interference is identical for simple nouns and noun-noun compounds, meaning the effect is not influenced by the morphological complexity of the targets. We will return to this issue in the General discussion. Furthermore, the results of the main analysis showed that cumulative interference robustly survives multiple repetitions of the same items, in line with results from previous studies [27, 28, 34]. However, when investigating the influence of Lag on cumulative interference, we observed an interaction between Lag, Ordinal position and Repetition, suggesting that cumulative interference is not entirely unaffected by repetitions. Although previous studies have shown that cumulative interference is not affected by lags of less than eight intervening items between members of a category [e.g., 18, 26, 29], our results suggest that this changes when participants repeat responses several times. After multiple naming cycles of the same targets, longer lags seem to induce weaker interference than shorter ones. This suggests that general repetition priming induced by naming items multiple times [68, 69] affects the build-up of interference in the long lag- condition to a greater degree that in the short-lag condition. This is compatible with the idea that cumulative interference dissipates over time, put forward by Schnur [33]. She showed that cumulative interference does not survive multiple long lags (8–12 intervening trials), unless short lags are inserted that amplify interference within semantic categories [see Exp. 3 in 33]. In the current study, the strong and long-lived facilitation induced by repeating identical targets [68, 69] increases each time a target is named (main effect Presentation). In later presentations, this built-up facilitation affects cumulative interference at long lags (6 or 8) to a larger degree than at short lags (2 or 4), as cumulative interference dissipates over lags, and is thus more easily cancelled out by the facilitation.

Experiment 2

Experiment 2 uses a non-verbal semantic classification task, including the identical picture stimuli as Experiment 1. Participants were instructed to indicate via button press whether a presented picture showed a natural or a man-made entity. It was designed to investigate semantic-conceptual processing of the experimental materials. We expected to replicate cumulative semantic facilitation, that is, a linear decrease of reaction times within semantic categories [30]. The aim was to better understand cumulative facilitation and its similarities and differences to cumulative interference observed in picture naming. To this end, we also investigated whether the cumulative facilitation effect could be predicted by cumulative interference, which would suggest a functional link between the two. This is important to make further inferences about the functional origin of cumulative context effects.

Material and methods

Participants, materials, apparatus, experimental design. Participants, materials, apparatus and experimental lists were identical to Experiment 1. Each participant first completed Experiment 1, and, after a break of approx. 15 to 20 minutes, continued with Experiment 2. When choosing the experimental items for Experiment 1 and 2, care was taken that targets as well as filler and practice items included an equal number of natural and man-made stimuli. Furthermore, when constructing the experimental lists, we ensured that there were no more than five man-made or natural items in a row to avoid bias in the classification task. Each participant was presented with the same lists as in Experiment 1.

Procedure. In the experimental session, a fixation cross was presented for 500ms at the start of each trial, followed by the picture. The picture was presented until a response was initiated or for a maximum of 2500 ms. After an inter-trial interval of 2 seconds, the next trial started. Participants were instructed to indicate via button-press whether the pictures depicted natural or man-made items. Reaction times were recorded from picture onset and incorrect responses were automatically coded.

Analysis

The data analysis of the classification task (software, packages, contrast-coding, transformation and model selection procedure) in Experiment 2 was identical to Experiment 1, with two exceptions. First, based on previous studies [e.g., 30], we included the factor classification type (man-made vs natural) as an additional predictor into the analysis. Second, we slightly changed the a-priori screening for artefactual responses after visual inspection. In this experiment, we defined outliers as reaction times shorter than 250 ms and longer than 2000 ms. Again, only experimental trials were included in the analysis. 8.0% of the trials were excluded because participants had either incorrectly classified the items (7.5%) or did not respond within the time limit (0.5%). A further 0.5% of the trials were identified as outliers. Of the remaining data, 1.8% were excluded after model fitting (standardised residuals > 2.5), leaving 89,7% of the initial data points to be included in the analysis. The final model used for the main analysis included an interaction of the predictors Word type produced in Experiment 1 (compound vs. simple noun) and Ordinal position (five ordinal positions of category members), an interaction of Presentation (Presentations 1–5, i.e., first classification cycle and four repetitions with different lists) and Ordinal position, an interaction of Semantic similarity (rating values) and Ordinal position, a three-way interaction of Semantic similarity, Ordinal position and Presentation, an interaction of Ordinal position and Classification type (man-made vs. natural), as well as main fixed effects for all predictors, and Trial number (consecutive trial number) as a covariate. The random structure included random intercepts for Subjects, Semantic categories and Items nested under Semantic categories, random slopes per subject for the interaction of Word type and Ordinal position, as well as for Word type, Ordinal position, Presentation, Semantic similarity and Classification type (omitting correlations to facilitate convergence). Furthermore, it included random slopes for Presentation for the random factor Semantic category.

In a second analysis we included the factor Lag (number of intervening items between the category members on Ordinal position 1–5) as an additional predictor in the above-mentioned model to investigate its influence on cumulative facilitation, following the same procedure as in Experiment 1.

To test whether the facilitation observed in the classification task can be predicted by the interference observed in picture naming, we conducted a third analysis. For that, we first computed both context effects by calculating the reaction time difference (difference score in ms) between Ordinal position 1 and 5 for each subject, category and presentation for each of the tasks. Categories for which no facilitation effect or no interference effect could be computed due to missing were excluded from the analysis (24.3% of trials). The facilitation effect as dependent variable was log- transformed, while the interference effect as one of the independent variables was centred. Both were included in a linear mixed model containing Presentation (centred), Semantic similarity (mean semantic similarity for each category, centred) and Word type as additional main fixed effects as well as two-way interactions between Interference effect and Presentation, Interference effect and Semantic similarity, Interference effect and Word type, and a three-way interaction of Interference effect, Presentation and Semantic similarity. Subjects were included as random factor to account for by-subject variance. Model comparisons were performed until the best fitting model (above) was identified (following the procedure described for Experiment 1).

Results

Table 2 shows the statistical results of the main analysis of the classification task. Overall, participants' response latencies decreased with each repetition (main effect Presentation). There was no main effect for Word type, indicating that participants took equally long to classify objects that were previously named using a compound or simple noun (mean RTs: 595.2 ms and 587.1 ms respectively). There was a main effect for Ordinal position: within semantic categories, participants' reaction times systematically decreased with each additionally classified picture (overall decrease from Ordinal position 1 to 5: 21 ms, see Fig 3 for a visual illustration). While this facilitation effect did not significantly differ as a function of word type (interaction: Word type*Ordinal position), it varied across repetitions (interaction: Ordinal position*Presentation). Separate post-hoc analyses of each of the five presentations revealed stronger facilitation (i.e., main effect for Ordinal position) in the first presentation (59ms between category member 1 and 5; $t = -5.80$, $p < 0.001$) than in presentations 3 to 5 (Rep3: 20ms; $t = -2.46$, $p = 0.019$; Rep4: 16ms; $t = -2.23$, $p = 0.026$; Rep5: 15ms; $t = -2.16$, $p = 0.037$) and no significant effect in Presentation 2 (14ms; Rep2: $t = -0.62$, $p = 0.54$, see Fig 4 for a visual illustration). Furthermore, we found a marginally significant interaction of Ordinal position and Classification type (man made—nature made). Separate post-hoc analyses for the two classification types

Table 2. Main model Experiment 2. -1000/RT ~ Word type*Ordinal position + Ordinal position *Presentation+ Ordinal position: Semantic similarity: Presentation + Ordinal position: Semantic similarity + Semantic similarity + Ordinal position *Classification type+ Trial+(Word type* Ordinal position +Presentation+ Semantic similarity +Classification type||Subject) + (1|Category/Item)+ (0+Presentation||Category).

Predictors	-1000/RT			
	Estimates	*std Error*	*t-value*	*p-value*
(Intercept)	-1.846	0.047	-39.48	<0.001
Word type	0.006	0.037	0.17	0.87
Ordinal position	-0.044	0.009	-4.88	<0.001
Presentation	-0.099	0.009	-10.90	<0.001
Semantic similarity	-0.032	0018	-1.80	0.073
Classification type	0.007	0.035	-0.19	0.849
Trial	< -0.000	<0.000	-1.794	0.080
Word type * Ordinal position	0.024	0.016	1.50	0.140
Ordinal position * Presentation	0.012	0.004	2.69	0.007
Ordinal position* Semantic similarity	0.025	0.013	1.92	0.06
Ordinal position* Classification type	0.022	0.013	1.75	0.081
Ordinal position* Presentation * Semantic similarity	0.022	0.009	2.54	0.011

Random Effects

	Variance	**Sd**
Subject (Intercept)	0.06	0.1
Subjects (Word type)	0.02	0.13
Subjects (Presentation)	< 0.01	0.05
Subjects (Ordinal Position)	< 0.01	0.04
Subjects (Semantic similarity)	< 0.01	0.04
Subjects (Word type * Ordinal position)	< 0.01	0.05
Subjects (Classification type)	0.01	0.12
Category (Intercept)	< 0.01	0.08
Category \ Item (Intercept)	< 0.01	0.05
Category (Presentation)	< 0.01	0.02
Residuals	0.11	0.34

https://doi.org/10.1371/journal.pone.0268915.t002

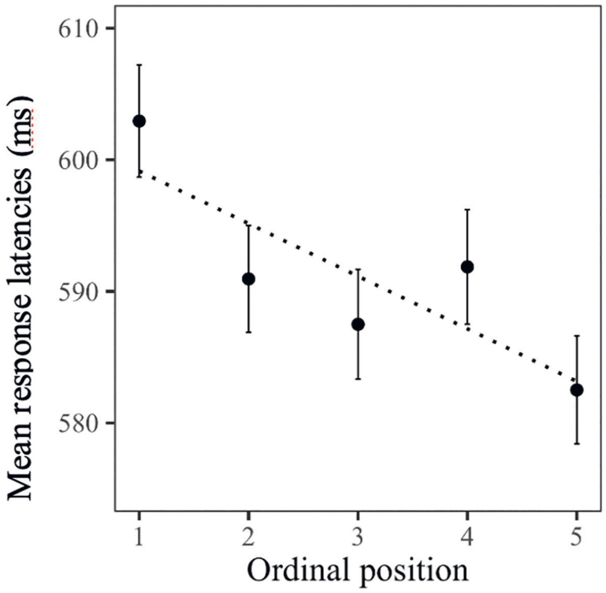

Fig 3. Mean reaction times (response latency) and standard error (in milliseconds) observed in Experiment 2 broken down by ordinal position.

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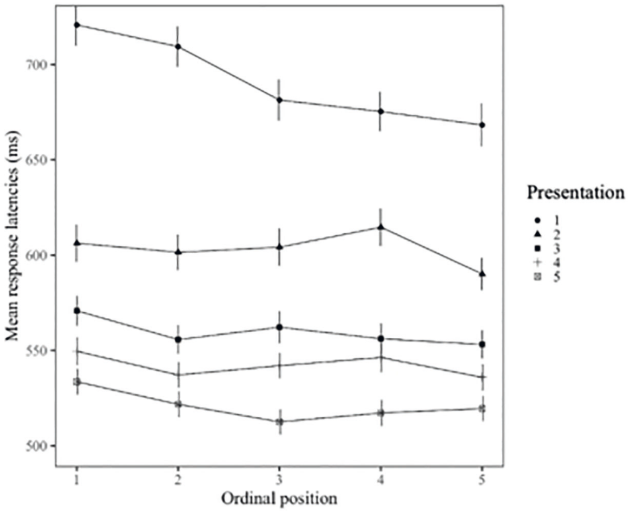

Fig 4. Visual representation of the facilitation effect in all five presentations.

https://doi.org/10.1371/journal.pone.0268915.g004 revealed that natural items induced stronger facilitation (*t* = -6.38, $p < 0.001$) than man-made ones (*t* = -3.77, $p < 0.001$). In the main analysis, we only found a marginally significant effect for the influence of semantic similarity on the ordinal position effect (Interaction: Ordinal position*Semantic similarity) but also found that this was influenced by repetition (interaction: Ordinal position*Presentation*Semantic similarity). The above-mentioned separate analyses of the five presentations showed that semantic similarity did not influence cumulative facilitation in the first three presentations (all interaction terms $p > 0.05$) but more strongly related items induced weaker facilitation than more weakly related ones in the last two presentations (Presentation 4: *t* = 2.13, *p* = 0.03; Presentation 5: *t* = 2.16, *p* = 0.03; see S2 Fig in S2 Appendix for a visual illustration).

The second analysis including Lag as an additional predictor revealed a main effect for Lag (t = 4.83, p <0001), with short lags predicting faster response times, but no significant interaction with Ordinal position (t = -0.95, p = 0.35) nor with Ordinal position and Presentation (t = -0.23, p = 0.822).

S1 Table in S2 Appendix contains the results of the LMM-analysis for the third analysis of the classification task data, in which we use the interference effect (Exp. 1) as a predictor for the facilitation effect (Exp. 2). The results show a main effect for the factor Interference effect (*t* = 2.36, *p* = 0.019), indicating that strong interference predicts weak facilitation. There was also a main effect of Presentation (*t* = 2.94, *p* = 0.003) but no interaction of the two (*t* = -0.69, *p* = 0.49). Furthermore, we found no main effect for Word type but a significant interaction of Interference effect and Word type, suggesting that the Interference effect does not predict the facilitation effect equally for the two word types. Separate post-hoc analyses for the two word types confirmed that the interference effect can only predict the facilitation effect of those items that were named as simple nouns (t = 2.74, p = 0.006) but not for compounds (t = -0.91, p = 0.36), as visualised in Fig 5. While there was no main effect for Semantic similarity, both the two-way interaction with Interference effect (*t* = -2.08, *p* = 0.038) and the three-way interaction with Interference effect and Presentation (*t* = 3.95, $p < 0.001$) were significant. The direction of the effects suggests that strong interference predicts weak facilitation for more loosely related items, but not for closely related ones, and that this prediction becomes weaker with each presentation. However, as the post-hoc analyses above showed that only the facilitation of the simple nouns can be predicted from the interference effect, it seems more appropriate to only take the simple-noun data into account when investigating the influence of semantic similarity on the ability to predict the facilitation from interference. Therefore, in an additional analysis, only the simple noun data was analysed. We found a significant interaction between Interference effect and Semantic similarity (*t* = -2.03, *p* = 0.04) and the visual inspection of the interaction confirms that a strong interference effect predicts a weak facilitation effect only for weakly-related category members but not for closely related ones (see Fig 6). The three-way interaction between Interference effect, Semantic similarity and Presentation was not significant (*t* = 0.50, *p* = 0.62).

Discussion

In Experiment 2, we replicated the cumulative facilitation effect reported by Belke [30]. Participants' response latencies systematically decreased within semantic categories with each classified picture (about 5ms from one picture to the next), independent of whether the pictures were named with a compound or a simple noun in the preceding picture naming task. However, we also found that this cumulative facilitation effect was influenced by repetition. While we observed a facilitation effect of nearly 15 ms (from one category member to the next) in the first classification cycles, in the subsequent four repetitions (Presentations 2–5) we observed

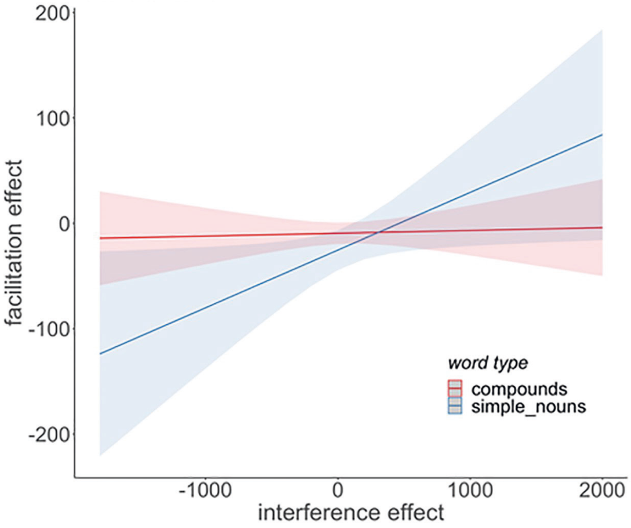

Fig 5. Predicted facilitation effect of Experiment 2 (in ms) by the interference effect observed in Experiment 1 (in ms), broken down by word type condition. Interference can only predict facilitation of simple nouns but not of compounds.

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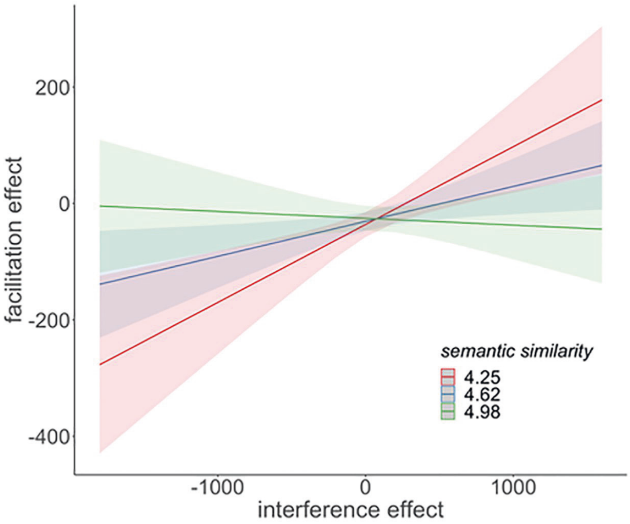

Fig 6. Depiction of the interaction of Interference effect and Semantic similarity found in the analysis for simple nouns. A strong interference effect (x-axis, in ms) predicts a weak facilitation effect (y-axis) but only for items that are less-closely related.

https://doi.org/10.1371/journal.pone.0268915.g006 much weaker ones of 4 to 5ms. In fact, Presentation 2 showed no significant facilitation, although response latencies between the first and last category members decreased nearly as much as in Presentations 3–5. To better understand the effect found in Presentation 2, we reran its analysis, this time including the cubic and quadratic trends in addition to the linear one. The results revealed a significant cubic trend (t = -2.26, p = 0.02), mirroring the visual effect depicted in Fig 4. Overall, these results show that cumulative facilitation seems to be more vulnerable to repetitions than cumulative interference, which extends previous findings on cumulative facilitation [30, 70] and provides additional insights into the characteristics of this effect. We will discuss this further in the General Discussion. Furthermore, we found that semantic similarity does not modulate cumulative facilitation in the same way as cumulative interference, with less closely related items inducing greater facilitation after several repetitions. This, again, shows the large influence of repetition on cumulative facilitation and all its modulating factors. However, as we also found semantic similarity to be a modulating factor of whether or not interference can predict facilitation, we will discuss both aspects related to semantic similarity in the General Discussion.

Interestingly, the results also show that natural and man-made items induce different levels of facilitation, with marginally stronger cumulative facilitation for the former than the latter. This is in line with results reported by Belke [30, Exp. 1]. She also found stronger facilitation for natural than for man-made objects but explained that the effect in her study is likely due to a response bias caused by unequal numbers of natural and man-made items (38 and 61%, respectively). In our experiment, the number of man-made and natural objects were perfectly balanced for targets and fillers, thus, there must be another cause underlying the effect. A closer look at the items revealed that natural objects overall had a significantly higher semantic similarity rating within their categories than man-made objects (Mean rating natural: 4.36; Mean rating man-made: 4.55, t = 22.29, $p < 0.0001$). As this might lead to stronger co-activation between natural objects overall, this is a likely cause for the different levels of facilitation for the two classification types. However, it has also been theorised that the processing of natural and man-made entities substantially differs and that natural entities are somewhat advantaged [71]. Karst and Clapham [72], for example, recently showed that priming is stronger for natural than man-made entities and report that this is partly due to their perceptual properties and familiarity. This might also explain the observed difference in facilitation between the two classification types in our study.

The second analysis of Experiment 2 revealed that cumulative facilitation is independent of the number of intervening items between category members (factor Lag), showing that the longevity attributed to cumulative interference can also be attributed to cumulative facilitation [see also 30]. The fact that we found shorter lags to positively influence overall naming latencies independent of category membership was likely caused by the way the experimental lists were constructed. Short lags mean multiple items of the same classification type (man-made or natural) in close proximity, as all members of a category are of the same classification types. Thus, priming of natural or man-made features is particularly strong, resulting in fast response times of items of the same classification type, independent of their semantic category.

The third analysis of the classification data shows that the cumulative interference effect observed in picture naming can predict the magnitude the cumulative facilitation effect observed in semantic classification of the same targets. This suggests a strong interplay between the two effects and, in turn, supports the claim that both cumulative context effects originate at the conceptual level [9, 30]. As the direction of the effect was rather unexpected and relates to both context effects, we will discuss this aspect further in the General Discussion. However, this leaves open the question why the interference could only predict the facilitation of targets named earlier with simple nouns but not those named with compound words. Please note: As we initially found this result rather surprising, we ran post-hoc correlation analyses of the data (Spearman's rank correlation as our data was not normally distributed) just to confirm the results of the linear-mixed model. And indeed, we found a significant positive correlation of cumulative interference and cumulative facilitation per subject for simple nouns ($r = 0.50$, $p = 0.002$) but not for compounds ($r = -0.05$, $p = 0.78$). It has been reported that participants prefer categorising and naming objects at the basic level (corresponding to our simple noun targets), and that object classification is faster at the basic level than at subordinate level (corresponding to our compound targets) or superordinate levels [e.g., 65, 66, 73]. Furthermore, it has been argued that the semantic classification task does not necessitate deep, fine-grained semantic processing of information that helps distinguish one category member from the other, or a basic level concept (table) from a subordinate level one (kitchen table), as all category members are either natural or man-made [e.g., 74]. Thus, one possible explanation for our result pattern is that participants processed the depicted objects at the basic level (simple noun concept, e.g., *table* instead of *kitchen table*) in the classification task, independent of how targets had been previously named. As the facilitation effect within categories would then be the result of co-activated basic-level concepts only (*table*, *shelf*, *bed* . . .), its effect size might only be predicted by the activation pattern of the exact same concepts in the picture naming task, namely by basic-level, simple noun names (*table*, *shelf*, *bed*) but not by compound names (*kitchen table*, *bookshelf*, *canopy bed*). However, further research is necessary to confirm this hypothesis.

General discussion

The aim of the current study was to gain a more comprehensive understanding of cumulative semantic interference. Experiment 1 was a continuous picture naming task designed to investigate whether the magnitude of the effect differs for morphologically complex noun-noun compounds (*kitchen table*, *bookshelf*) and morphologically simple nouns (*table*, *shelf*). The results are clear-cut: While compounds have overall longer naming latencies than simple nouns, both word types induce identical levels of cumulative interference. This study thus provides first evidence that cumulative interference is not affected by morphological complexity. While we predicted that the interference might be weaker for compounds than for simple nouns due to their potentially more complex lemma structure and the fact that the first constituent is not semantically related to the compound's semantic category, the results suggest that the co-activation of semantically related concepts, and thus the interference effect, was mainly driven by the compounds' semantically related second constituents. Any activation that might have dissipated via the unrelated first constituent did not significantly weaken the co-activation of related concepts. As our data thus show that cumulative interference is not affected by morphological complexity.

Please note that we used identical picture stimuli in both word type conditions to minimise potential influences of visual effects on naming times [75]. Thus, one could assume that the identical results in both word type conditions could also be the result of identical visual input leading to the activation of the same conceptual information in both conditions, and thus identical interference. This, however, could not have been the case, as participants would have otherwise produced the same output. After all, to either produce a noun-noun compound or a simple noun, the corresponding conceptual information and lemma(s) for each word type needed to be activated [6, 8, 9 and many others].

While we initially conducted this experiment to investigate the influence of morphological complexity on cumulative interference, the results might also be indicative of the location of the learning mechanism responsible for the effect (i.e., its origin). If it was located at the interface of the conceptual and the lexical (i.e., lemma) level, one might expect that the lemma representation of the targets influences cumulative interference. More specifically, as we assume different representational formats for compounds and simple nouns [27, 46, 47 but see 43], different magnitudes of cumulative interference should have been observed. This is because in the simple noun condition, the learning mechanism responsible for cumulative interference would only strengthen the connection between the conceptual representation (SHELF) and the one corresponding lemma representation [*shelf*; 22] and potentially weaken the connections to other related targets [29]. In the compound condition, however, multiple lemmas are involved in the production process, the holistic compound lemma (*bookshelf*) as well as the constituent lemmas [*book* and *shelf*; 27, 46]. Thus, the learning mechanism might not only affect the links between the conceptual representation (BOOKSHELF) and the corresponding holistic lemma (*bookshelf*) but also the direct links between the holistic lemma (*bookshelf*) and the constituent lemmas (*book* and *shelf*), and possibly even the links between the constituent lemmas (*book* and *shelf*) and their conceptual representation (BOOK and SHELF). This might affect the activation pattern during compound naming and thus impact on the magnitude of interference that accumulates within categories. If, however, the learning mechanism responsible for cumulative interference was located at the conceptual level itself, implemented as strengthened links between the lexical concept and its features [9, 30], we would expect similar patterns of cumulative interference in both word type conditions. Although the compounds represent more specific concepts compared to the simple nouns, the main features corresponding to a certain semantic category (e.g., furniture: non-living, is wooden, part of a house . . .) are identical for both (SHELF and BOOKSHELF). Thus, a learning mechanism at this level is likely to induce similar cumulative interference for both word types, which is what we observed. This, however, is a post-hoc interpretation of the results and none of the above-mentioned models actually addresses this issue. Nonetheless, this discussion might provide inspiration to consider lexical information of the targets to further investigate the origin of cumulative interference.

Experiment 2 was designed to gain a more comprehensive understanding of the cumulative facilitation found in semantic classification tasks and thus to contribute further to the discussion about the functional origin of cumulative context effects. In this study, we observed the expected cumulative facilitation reflected by a systematic decrease in response latencies within semantic categories, replicating the effect first reported by Belke [30]. We thus provided additional evidence that facilitatory cumulative effects can arise in purely semantic tasks that do not necessarily involve the lexical system. Furthermore, our additional analysis showed that the size of the interference effect found in picture naming can be used as predictor for the facilitation effect of the (simple noun) targets in the classification task, which suggests that both context effects are functionally linked. This replicates previous findings which showed that cumulative interference and cumulative facilitation can influence one another when picture naming and picture classification alternate within an experiment [30, Exp. 5]. Our results thus seem to support accounts that localise the functional origin of cumulative interference at the conceptual level [9, 30]. Models locating the origin at the interface between the conceptual and lexical level [22, 29] can, in their present state, not easily account for cumulative facilitation, as their incremental learning mechanisms responsible for cumulative effects necessarily involves the activation of lexical information. In a comment, however, Oppenheim argued that the model presented in [29] could be altered for the classification task, namely that the learning mechanism affects links between man-made/natural features and man-made/natural response nodes instead of the links between the concepts and the lexical nodes [see 30, p.253]. However, only a computational implementation of the proposed changes can show whether this would indeed result in the observed result pattern found in the classification task as well as the interplay between interference and facilitation observed in this study. Howard et al. [22] would have to adjust their model even further. In its current form, the proposed learning mechanism only comes into effect when a lexical representation has been selected, which is very unlikely the case in a purely semantic classification task. Thus, they would have to adjust their learning mechanisms in such a way that it does not require actual retrieval but only the activation of lexical information [30; for experimental evidence along those lines, see 76]. This, of course, would only explain cumulative facilitation if the lexical level was indeed activated during the classification task.

While the discussion thus far suggests straightforward results that are more easily explained by models assuming a purely conceptual origin of cumulative interference than those assuming an origin at the interface between the conceptual and lexical level, two findings complicate matters. First, our results show that cumulative facilitation is more strongly affected by repetitions than cumulative interference. While one could argue that this suggests different underlying mechanisms of the two effects which might advocate against a common origin of both effects, we believe that the differences are task specific. It is likely that weak cumulative facilitation after the first classification cycle is due to a ceiling effect in the activation of category-related nodes induced by the persistent activation of man-made/natural features, meaning it is related to the task at hand. After the first classification cycle, the connections between man-made/natural features and all items should have been strengthened [30]. In the subsequent classification cycles, each man-made/natural entity would thus receive some activation when an item of the same type (either man-made or natural) is being classified, even when they do not belong to the same semantic category. This constant activation might exceed any additional activation that the items receive from categorically related items. This would result in overall faster classification times but only a weak accumulation of facilitation within categories, which is what we observed in Presentations 2 to 5. In addition, the general facilitation induced by repetition priming we found in our analysis (main effect for Presentation) adds to the overall enhanced activation levels in subsequent classification cycles, further adding to the ceiling effect. To avoid the constant activation of the same features and to make the classification task and the naming task more similar, one would have to alter the classification task in such a way that participants are required to classify the items into a larger number of classification categories. And even then, general repetition priming might dampen the facilitation effect within categories still more than the interference effect in the naming task, as the effect size of the former is much smaller than that of the latter. However, there might be another task and order-related reason for the strong influence of repetition on cumulative facilitation, as pointed out by Eva Belke during the review process. We initially thought that the decrease of facilitation after the first classification cycle cannot simply be attributed to the fact that activation levels at the conceptual level were exhausted because participants were exposed to the visual stimuli too many times. This was because participants completed an additional round of continuous naming (one naming cycle) after the classification task, and the results mirrored those of the main naming task: robust cumulative interference that did not differ between the two word types (for more details, see S2 Table and S3 Fig in S2 Appendix). While this additional naming cycle at the end of the experimental session is not of central importance for this study, we initially interpreted it as evidence that the stimuli were still sensitive to semantic context effects, even after multiple repetitions. However, it is possible that participants became increasingly aware of the semantic categories due to repeatedly seeing the same items. This is unlikely to have a significant impact on picture naming, as each target still needs fine-grained conceptual processing to distinguish it from other category members, resulting in robust cumulative interference even after being exposed to the targets several times. However, it might have impacted the classification of targets by creating expectations. This might have let to even more superficial processing of the targets and thus to a decreasing co-activation of semantically related concepts. So, while the influence of repetition clearly differs for cumulative interference and cumulative facilitation, it is likely due to be task-inherent difference rather than inherently different characteristics of the two effects. This, of course, needs to be confirmed by future research.

A second finding that is, at first glance, not easily embedded in the rationale of existing models is that strong cumulative interference in picture naming predicts weak facilitation of simple nouns in the classification task. While this suggests a functional link between the two, the direction of the effect is rather surprising. Please note that we were able to replicate this pattern in a follow-up study. Based on the working model proposed by Belke [30], we initially would have predicted mirroring effects, namely stronger interference predicting stronger facilitation. However, these expectations were built on the rationale that the effect in the naming task was based on conceptual facilitation that turned into interference at the lexical level, and that this facilitation would be identical to the facilitation found in the classification task. In hindsight this may be an oversimplification of the actual processes and there might be multiple explanations for the observed pattern.

First, our initial prediction did not take into account the different tasks that bring to bear the two effects. Assuming a conceptual origin of the effects [30], the accumulating interference in picture naming results from the co-activation of category members and the strengthening of the connections between those members and their semantic features after successful naming. Here, deep processing of all semantic features is key to perform the task. Only if all features are activated, in particular those that are unique to the target and distinguish it from their category members, can one produce the intended category member (see also 30]. In the classification task, on the other hand, only those features are relevant that identify the target as either man-made or natural, which are shared by all members of a category. As argued in the discussion of Experiment 2, fine-grained semantic processing is not essential to perform the classification task [e.g., 30, 70], and quite possibly even disadvantageous as it may delay the response. Thus, the facilitation observed in the classification task is not identical to the facilitation responsible for the interference in the naming task, which might explain why our initial predictions did not pan out.

Secondly, it is possible that the order in which participants completed the two tasks directly influenced the results of the classification task, both with respect to how cumulative facilitation is predicted by the interference effect as well as how it is influenced by semantic similarity. In the naming task, focusing on the unique features of a target (i.e., those it does not share with other category members) is key to complete the task, namely to select one specific target from among a group of (co)activated items. After successfully naming the target, the links between its features and its lexical representation would be strengthened (i.e., learning mechanism). In picture naming, this mechanism leads to the observed interference, as the strengthened links render the target a strong competitor in the naming process of a to-be-named category member. In the following classification task, however, these strengthened unique links will make it increasingly difficult to focus on the shared features of the target, which are key to complete the classification task. Thus, categories that induced strong interference would then induce weaker facilitation than if the target had not previously been named (and no unique features had previously been strengthened). This would also explain why we observed weaker cumulative facilitation for more strongly related category members (i.e., high semantic similarity) in Experiment 2. This rationale is based on results reported by Belke [30]: In Experiment 5, semantic classification and picture naming were mixed, and in the classification task attenuated facilitation was observed after an item was named. Belke argues that this was due strengthening of the unique features after naming, which attenuated the facilitation effect in the classification task, as this is based on the shared features of the category members. However, until there is a computational implementation of the working model proposed by Belke [30], the above explanation of the results remains speculation.

Conclusion

The aim of the current study was to contribute to a more comprehensive understanding of cumulative context effects found in picture naming and picture classification. From two experiments, we reported three main findings: 1. Cumulative interference does not significantly differ for morphologically complex noun-noun compounds and morphological simple nouns, suggesting that the effect is not influenced by the morphological complexity. 2. We replicated previous findings that cumulative effects can also be found in purely conceptual tasks, expressed as cumulative facilitation, and 3. we showed that cumulative interference can be used to predict cumulative facilitation. Our results thus indicate a purely conceptual-semantic origin of cumulative context effects, including the much-debated cumulative interference.

Supporting information

S1 Appendix.
(DOCX)

S2 Appendix.
(DOCX)

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Author Contributions

Conceptualization: Anna-Lisa Döring, Rasha Abdel Rahman, Pienie Zwitserlood, Antje Lorenz.

Data curation: Anna-Lisa Döring.

Formal analysis: Anna-Lisa Döring.

Funding acquisition: Antje Lorenz.

Investigation: Anna-Lisa Döring.

Methodology: Anna-Lisa Döring, Rasha Abdel Rahman, Pienie Zwitserlood, Antje Lorenz.

Project administration: Anna-Lisa Döring, Antje Lorenz.

Resources: Rasha Abdel Rahman, Antje Lorenz.

Supervision: Rasha Abdel Rahman, Antje Lorenz.

Validation: Anna-Lisa Döring.

Visualization: Anna-Lisa Döring.

Writing – original draft: Anna-Lisa Döring.

Writing – review & editing: Rasha Abdel Rahman, Pienie Zwitserlood, Antje Lorenz.

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The electrophysiological signatures of cumulative semantic interference and facilitation point to a common conceptual origin

Anna-Lisa Döring[1], Rasha Abdel Rahman[1], Pienie Zwitserlood[2] & Antje Lorenz[1]

[1]Department of Psychology, Neurocognitive Psychology, Humboldt-Universität zu Berlin

[2]Department of Psychology and Otto Creutzfeldt Center for Cognitive and Behavioral Neuroscience,
Westfälische Wilhelms-Universität Münster

Corresponding author:

Anna-Lisa Döring, Humboldt-Universität zu Berlin, Department of Psychology,

Rudower Chaussee 18, 12489 Berlin, Germany.

Phone: +49 – 30 – 2093-4904

Email: anna-lisa.doering@hu-berlin.de

Abstract

When naming a sequence of pictures of the same semantic category, latencies increase with each named category member. This cumulative semantic interference effect has become a popular tool in speech production research. While the locus of the effect, meaning the level at which cumulative interference comes into effect and behavioural consequences arise, is said to be the lexical level, it is still under debate where the effect originates. Some argue for an origin at the interface of the conceptual and lexical level, while others assume a purely conceptual origin. The latter is supported by the finding that cumulative effects, such as cumulative facilitation, can also be observed in purely conceptual-semantic tasks. The current ERP-study aims to contribute to this debate by investigating the time course and topography of cumulative interference and cumulative facilitation.

We studied the semantic context effects in two EEG experiments, using continuous picture naming and continuous semantic picture classification. In picture naming (three repetitions), we observed cumulative interference in the behavioural data, indexed by the typical increase of naming latencies. In the ERPs, cumulative interference was reflected by a posterior positivity starting around 250ms post picture onset, followed by a posterior negativity starting around 450ms. Contrary to most other continuous picture naming studies, we found cumulative interference to be influenced by item repetition in the behavioural and EEG data. In semantic classification, where participants classified the object via button-press as either man-made or natural (three repetitions), we observed cumulative facilitation in the behavioural data as decreasing reaction times within semantic categories. In ERPs, cumulative facilitation was reflected by a semantic effect (reduced N400) starting around 350 ms post picture onset, and a posterior negativity with the same temporal and spatial distribution as in picture naming. Like cumulative interference, cumulative facilitation was strongly influenced by repetition. The commonalities between the two context effects observed in the behavioural and electrophysiological data suggest that they are functionally linked, which points to a purely conceptual origin of cumulative interference and cumulative facilitation.

Keywords: language production; continuous picture naming; cumulative interference; semantic classification; cumulative facilitation, EEG

1. Introduction

It is well-established that the context in which a to-be-named stimulus appears affects its processing speed and accuracy in language production. For example, when naming a sequence of pictures that includes several members of the same semantic category (e.g., mammals: dog, cat, mouse, donkey, horse), naming latencies systematically increase with each named member of that category (e.g., Howard et al., 2006). This so-called cumulative semantic interference (CSI) effect occurs during lexical-semantic encoding, when a concept is mapped to its name. As it provides insights into the architecture of our speech production system, more specifically into the processes involved in lexical-semantic encoding, the CSI effect has become a popular tool in speech production research. It has, for example, been used to investigate lexical selection in social settings (Hoedemaker et al., 2017; Kuhlen & Abdel Rahman, 2017, 2021), lexical access in bilinguals (Runnqvist et al., 2012), the lexical representation of morphologically complex words (Döring et al., 2022b), semantic integration of newly acquired words (Oppenheim, 2018), or whether or not lexical selection is a competitive process (Howard et al., 2006; Navarrete et al., 2010; Oppenheim et al., 2010). Despite its extensive use, not all aspects of the effect itself are fully understood. It is still unclear where in the language production system the CSI effect originates (Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010; Roelofs, 2018). There is also still little known about the commonalities and differences of cumulative interference and other cumulative context effects, such as cumulative facilitation observed in semantic classification tasks (Belke, 2013; Döring et al., 2022a; Riley et al., 2015). This is particularly true for the neurobiological underpinnings of such context effects. While very few studies looked at brain responses related to cumulative interference (Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017), to our knowledge, no study has done so for cumulative facilitation. In the current ERP study, we thus investigate the neurocognitive signatures of cumulative interference and facilitation, to gain a more comprehensive understanding of their timing and topographies, as well as their relation. This will shed light on the origin of cumulative semantic interference, which is essential because only on the basis of an accurate appraisal of the CSI effect can we make informed predictions when using it as a research tool in language production research.

1.1 The origin of cumulative semantic interference

CSI is a phenomenon observed in continuous picture naming, a task in which participants are presented pictures in a seemingly random order and are instructed to name them. Members from different semantic categories are included within this sequence of pictures (e.g., *apple, banana, pear, lemon, kiwi* of the category *fruits*), separated by at least two unrelated objects (either filler items or members from other semantic categories (Howard et al., 2006). Characteristically, participants' naming latencies within a semantic category linearly increase with each named member. For example, they take longer to name the picture of a banana when they previously named a picture of an apple, and even longer to subsequently name a picture of a pear. This CSI effect complements semantic interference observed in other speech production paradigms, such as the picture-word interference (PWI) paradigm (Damian & Bowers, 2003; Glaser & Düngelhoff, 1984; Glaser & Glaser, 1989; Schriefers et al., 1990; for a recent overview see Bürki et al., 2020) or the blocked-cyclic naming paradigm (Belke et al., 2005; Damian & Als, 2005; Damian et al., 2001; Kroll & Stewart, 1994; Lin et al., 2022; Schnur et al., 2006). Interestingly, CSI seems to be largely independent from the number of unrelated intervening items (from now on called *lag*; Howard et al., 2006), as long as the number does not regularly exceed eight (Schnur, 2014). Earlier studies also suggest that it survives multiple repetitions of the same items (Costa et al., 2009; Navarrete et al., 2010; Rose & Abdel Rahman, 2017). However, recent evidence from our lab suggests that repeating items can diminish the CSI effect (Döring et al., 2022b; Holtz et al., in prep.) and that item repetition might influence the longevity of the effect, with long-lag items inducing weaker interference than short-lag items after several repetitions (Döring et al., 2022a).

There are several speech production models attempting to explain the underlying processes of CSI that are responsible for its characteristic accumulating nature. Despite large differences, they all share two core assumptions of lexical-semantic encoding: 1. Lexical-semantic encoding involves at least two representational levels, a conceptual level and a lexical level, and 2. semantically related lexical entries are initially co-activated via spreading activation at the conceptual level (Collins & Loftus, 1975), before the lexical entry of the target word, as the most activated item, is selected from among this co-activated cohort (Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010; Roelofs, 2018; see also Abdel Rahman & Melinger, 2009; Caramazza, 1997; Dell et al., 1997; Levelt et al., 1999). It is assumed that the strength of cohort co-activation is directly modulated by the degree to which the concepts are semantically related, with stronger co-activation of more closely related items (e.g., Lin et al., 2021; Rose & Abdel Rahman, 2017). Furthermore, all models believe the locus of cumulative interference to be the lexical level, with locus referring to the level at which cumulative interference comes into effect and behavioural consequences arise. Here, CSI is said to reflect an increasing difficulty to select the target's lexical representation from among the cohort of co-activated lexical entries. However, activation within the lexical system is short lived and can thus not be responsible for the persistence of the effect over time, which results in the accumulation of interference within categories. It has therefore been proposed that the origin of cumulative interference effect must lie elsewhere, and that an additional mechanism, accountable for its longevity, must underlie the effect. Models on cumulative interference differ with respect to the effect's origin as well as the underlying mechanism.

Howard et al. (2006) and Oppenheim et al. (2010) both argue for an origin at the links between the conceptual and lexical level and believe that a learning mechanism, with long-term changes to the production system, is responsible for the longevity of cumulative interference. However, they differ substantially in other respects. Howard and colleagues assume that the links between the concept and its lexical representation are strengthened after the target's lexical representation has been selected for further processing. This learning mechanism makes the target more available for future naming (i.e., long-term repetition priming, see also Mitchell & Brown, 1988; Wheeldon & Monsell, 1992). When its concept is subsequently co-activated in the naming process of semantically related category members, its lexical representation is more strongly activated than previously unnamed items due to strengthened links. This makes the target a strong competitor in the lexical selection process of the to-be-named category member. In continuous picture naming, the number of strong competitors systematically rises with each additionally named category member, resulting in accumulating interference within the category (Howard et al., 2006). Thus, in this model, cumulative interference relies on long-lasting priming, co-activation and competition. The learning mechanism proposed by

Oppenheim and colleagues (2010) entails both reinforcement of links between conceptual and lexical representations of named items, and weakening of links between the conceptual and lexical representation of co-activated non-targets. When a non-target is the to-be-named object later on, these weakened links result in weaker activation of its lexical representation. This increases the time it takes to select its lexical representation, which can behaviourally be observed in longer naming latencies. Thus, the model presented by Oppenheim et al. explains cumulative interference without assuming competition during lexical selection (see also Dell, 1986; Navarrete et al., 2010)[1].

In contrast to these accounts, Belke (2013) and Roelofs (2018) assume a purely conceptual origin of cumulative interference, located at the links between the semantic features and the lexical concept (a unitary conceptual representation). Belke (2013) argues for a long-lasting learning mechanism by which links between a target's lexical concept and connected semantic features are strengthened once the target's lexical concept has been selected. These strengthened connections will increase co-activation of the target's lexical concept and thus its lexical representation when subsequently trying to name a semantically related category member. Thus, former targets will be strong competitors in the lexical selection process of a to-be-named category member, which will increase selection time and thus result in longer naming latencies. As each category member adds to the cohort of strongly activated lexical representations in the continuous naming paradigm, interference builds up within categories. Supporting her claim of a conceptual origin of CSI, Belke (2013) demonstrated that a cumulative context effect can also be observed in a purely semantic task in which the lexical level is not (necessarily) involved. In that task, participants classified objects from different semantic categories as either man-made or natural, and indicated their decision through pressing a button. Instead of cumulative interference, Belke observed cumulative facilitation:

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[1] In fact, the models by Howard et al. (2006) and Oppenheim et al. (2010) differ in two more aspects, which we only briefly mention here because they are not as essential for our current purposes. Howard et al. describe the conceptual level as containing holistic concepts (see e.g., Levelt et al., 1999), while Oppenheim et al. model the conceptual level as a collection of semantic features that together make up the meaning of a target word. They also differ in terms of the lexical level. Howard and colleagues follow Levelt et al (1999) and assume that the lexical level consists of two entities, the so-called lemma (an abstract entity containing the grammatical information of the word) and the word form (or lexeme). In their model, the lemma is the locus of cumulative interference, while the word form only gets activated once lemma selection is completed. Oppenheim and colleagues, on the other hand, argue for a single lexical representation and thus against the existence of a separate lemma entity.

Participants' reaction times linearly decreased within semantic categories with each classified category member. She argues that the man-made or natural distinctions become increasingly easy, as the semantic features related to either man-made or natural entities of a certain semantic category are repeatedly activated. Here, facilitation rather than interference is observed because the origin and the locus of the effect are both the conceptual level, which is linked to facilitatory rather than inhibitory effects. Furthermore, Belke (2013) demonstrated that cumulative interference and facilitation can interact when including picture naming and semantic classification in one task, which supports her claim that the two effects share a common origin at the conceptual level. Roelofs (2018) provides a similar model of cumulative interference. But unlike Belke (2013), he proposes a temporary bias towards the target's concept after selection instead of long-lasting changes to the links between lexical concept and semantic features. His computational simulation could model cumulative interference in naming with this bias, as well as the cumulative facilitation effect reported by Belke (2013). Roelofs argues that this temporary bias more readily explains the disappearance of cumulative interference when the lags between category-related pictures are consistently large (e.g., 6 or more, instead of 2 or 3 intervening items (Schnur, 2014, for converging results see Döring et al., 2022a). Thus, cumulative interference seems not as persistent as other long-lasting effects such as repetition priming, said to rely on a similar implicit learning mechanisms (Mitchell & Brown, 1988; Wheeldon & Monsell, 1992; Zwitserlood et al., 2000).

Models locating the origin of CSI at the interface of the conceptual and lexical level at present do not provide an explanation for cumulative facilitation found in the classification task, as they were solely designed to account for language production data (Howard et al., 2006; Oppenheim et al., 2010). As the classification task does not necessitate the activation of the lexical level, these models have a hard time explaining cumulative facilitation and its interaction with cumulative interference (Belke, 2013). Thus, a closer look at cumulative facilitation and its relation to cumulative interference is one way to advance the discussion on the origin of cumulative context effects. In a recently published study, we started doing just that (Döring et al., 2022a). Participants first completed a continuous picture naming task before classifying the same items as either man-made or natural. We were able to replicate cumulative interference in picture naming and, like Belke (2013; see also Riley et al., 2015), observed cumulative facilitation in the classification task. Although we found cumulative facilitation to be more vulnerable to repetitions than cumulative interference, our results point towards a common origin of the effects at the conceptual level. Using the interference effect as predictor for the facilitation effect, we showed that the strength of cumulative interference can predict the strength of cumulative facilitation, with strong interference predicting weak facilitation. While these results suggest a shared underlying mechanism, more research seems necessary to fully understand the commonalities and differences between the two effects. An effective way to investigate these issues is to gain insight into their temporal dynamics and topographies. To that end, the current study extracted event-related potentials (ERPs) from the electroencephalogram (EEG) acquired during continuous picture naming and continuous classification.

1.2 The neurocognitive signature of cumulative context effects

Few studies have investigated the neurocognitive signature of cumulative semantic interference (Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Llorens et al., 2014; Rose & Abdel Rahman, 2017), and two ERP components can tentatively be linked to the effect. First, an enhanced positivity at posterior electrode sites between around 200 and 400ms post-picture onset is positively correlated with reaction times (Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017; but see Llorens et al., 2014). This component has been linked to the lexical selection process. As this positivity linearly increases with each category member, it may reflect increased difficulty to select the target's lexical representation. The second component linked to cumulative interference is a later negativity, increasing with additional category members (Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017; but see Costa et al., 2009; Llorens et al., 2014). Rose and Abdel Rahman observed this negativity between 460 to 590ms after picture onset, at posterior sites. It was negatively correlated with behavioural cumulative interference. They suggest that this component, potentially belonging to the N400 family, might reflect the learning mechanism that is responsible for its longevity (i.e., strengthening of connections between semantic features and concepts (Belke, 2013) or between the conceptual and lexical level (Howard et al., 2006; Oppenheim et al., 2010)). While the above-mentioned EEG-studies asked participants to name the same items repeatedly to obtain a sufficiently large number of epochs for the analysis (Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017), only Costa and colleagues investigated the effect of repetition on the electrophysiological correlates of CSI. They found no significant influence of repetition on any ERP components.

To our knowledge, as yet no study investigated the electrophysiological correlates of cumulative facilitation. Semantic priming studies with different kinds of stimuli (pictures, visual/auditory words, auditory sounds) have identified the N400 component as being strongly influenced by context (for an overview, see Kutas & Federmeier, 2011). The N400 is a central-parietal negativity that peaks around 400 ms post-stimulus onset. In language comprehension, this negativity is enhanced when a target appears in an incongruent context as compared to a neutral context, and reduced in a semantic congruent context (e.g., semantic priming condition). Thus, the N400 is often interpreted as reflecting the degree of effort it takes to access and/or integrate semantic information (for a discussion, see Kutas & Federmeier, 2011). For example, when pictures are primed by pictures and the task is a relatedness judgement, a reduced N400 component on the target picture can be observed for semantically related compared to unrelated picture pairs (e.g., McPherson & Holcomb, 1999). Similarly, in a picture naming task with semantic primes, an attenuated N400 for semantically related word-picture pairs was reported either at centro-parietal electrodes sites, or broadly distributed (Blackford et al., 2012; Lorenz et al., 2021; Piai et al., 2014; Roelofs et al., 2016, Rose et al., 2019). Most relevant for the present purpose, studies employing a semantic classification task (e.g., man-made/natural distinction) found a reduced N400 with a temporo-parietal focus for pictures primed by semantically related compared to unrelated words (Dobel et al., 2010; Geukes et al., 2013). However, the N400 has not exclusively been linked to contextual semantic processing. In language comprehension, it also been found to reflect the depth of semantic processing, independent of context (Rabovsky et al., 2012b, 2012a). There, words with many semantic features elicited a larger N400 than those with fewer features (see also Amsel, 2011). These results are in line with others, showing that concrete words, which are assumed to contain richer semantic representations, produce a larger N400 than abstract words (e.g., Kounios & Holcomb, 1994; West & Holcomb, 1991).

1.3 The current study

The purpose of the current study is to gain a more comprehensive understanding of the commonalities and differences of cumulative interference in picture naming and cumulative facilitation in picture classification, to shed light on their origin. To do that, we investigated their neurocognitive signatures in two EEG experiments with the same group of participants, the same visual stimuli, but different tasks.

In Experiment 1, we investigated cumulative interference in a continuous picture naming task, including the influence of repetition on its electrophysiological and behavioural effects. Participants named pictures from different semantic categories three times each, while we recorded their naming latencies as well as the continuous EEG. Based on previous studies (e.g., Howard et al., 2006), we expected the participants' naming latencies to systematically increase within semantic categories (factor Ordinal position), reflecting the increasing difficulty to select the lexical representation of the target. In the EEG data, we expected to observe a posterior positivity (about 250-400ms post picture onset) followed by a posterior negativity (around 450-600ms post picture onset), reported by previous studies (Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017). While it has been reported that ERPs in continuous naming are not influenced by repetition (Costa et al., 2009), other studies have found that repeating items leads to a reduced brain response (e.g., Gruber & Müller, 2005) or a different activation pattern (e.g., Lorenz et al., 2021). Thus, we also investigate the influence of repetition on cumulative interference to better understand all factors modulating CSI.

In Experiment 2, we studied the electrophysiological correlates of cumulative facilitation in a semantic classification task. The same participants saw the same stimuli as in Experiment 1 and classified them via button-press as man-made on natural. Based on previous studies, we expected to observe cumulative facilitation, reflected by a systematic decrease of response latencies within semantic categories (Belke, 2013; Döring et al., 2022a; Riley et al., 2015). As this effect is said to reflect increasing ease to access semantic information, that is, semantic priming (Belke, 2013), we hypothesised that this behavioural effect would be accompanied by a reduced N400 effect for later category members compared to earlier ones. As N400 effects have been mainly observed at either central/posterior electrode sites or more broadly distributed (Geukes et al., 2013; Hamm et al., 2002; McPherson & Holcomb, 1999), we defined the same posterior electrode sites as in Experiment 1 as our region of interest [ROI] for Experiment 2. Choosing this ROI allowed us to test for N400 effects, but also whether the later posterior negativity found in continuous picture naming (450-600ms) can also be observed in the continuous classification. If this effect indeed reflects the learning mechanism responsible for the accumulation of interference in picture naming (e.g., Rose & Abdel Rahman, 2017), and if the same learning mechanism is responsible for cumulative facilitation (Belke, 2013), then we might also observe this late negativity in Experiment 2. Moreover, conceptual and lexical processes are likely to overlap in time and space (e.g., Abdel Rahman & Melinger, 2009, 2019; Belke, 2013; Roelofs, 2018), as recently shown in picture naming studies with EEG (Lin et al., 2022; Rabovsky et al., 2021). Thus, it logically follows to use similar electrode sites to investigate facilitatory effects at the conceptual level in semantic classification and inhibitory effects at the lexical level in picture naming. As in Experiment 1, we investigate potential interactions between cumulative facilitation and repetition.

In a previous study we found that cumulative interference can be used to predict cumulative facilitation, which points to a functional link between the two effects and thus to a conceptual origin of cumulative context effects (Döring et al., 2022a). In particular, stronger semantic interference in picture naming predicted weaker facilitation in the classification task. The current study aims to replicate our previous findings. In an additional analysis, we used cumulative interference observed in Experiment 1 as a predictor for the cumulative facilitation found in Experiment 2, as the classification task always followed the naming task in our experimental setting.

2. Experiment 1: Continuous picture naming

2.1 Material and methods

2.1.1 Participants

Thirty-six native speakers of German (25 female, 11 male) between the age of 18 and 35 (mean 27 years) were included in the analysis. Eight participants had to be excluded and replaced due to either technical problems, too many errors in either of the two tasks or because of excessive trial loss due to noisy EEG recordings. The sample size was chosen following a power analysis (simr package, Green & Macleod, 2016). Based on our previous study, we predicted an effect size (*b)* of about -0.04 for the cumulative facilitation effect and 0.09 for the cumulative interference effect in the behavioural data (Döring et al., 2022a). To ensure enough power to detect the weaker facilitation effect, we decided to run the power analysis for the classification task to determine the sample size. We simulated the outcome of the anticipated model with 1000 iterations and the above-mentioned *b* of -0.04. With 18 participants we reached a power estimate of 88% (95% confidence interval: 86.0, 90.13) for detecting the hypothesized cumulative facilitation in the classification task when presenting the participants with three experimental lists each. As we were planning on also investigating the influence of repetition on the two effects, we decided to double the number of participants to ensure enough power for these analyses. All participants were right-handed, had normal or corrected-to-normal vision and received monetary compensation or course credit for their participation. The study was approved by the local ethics committee of Humboldt-Universität zu Berlin, and is in accordance with the Declaration of Helsinki. All subjects gave informed written consent.

2.1.2 Materials

The stimuli set consisted of 130 coloured photographs of 65 man-made and 65 natural entities, including 90 targets, 30 filler items and 10 practice items. All picture names were monomorphemic nouns from the same stimulus set we used in our previous study (Döring et al., 2022a). The picture targets mapped onto 18 different semantic categories (e.g., tools), with five members each. As it is known that within-category semantic similarity modulates cumulative interference (Rose & Abdel Rahman, 2017), we conducted a pre-test to establish a measure of semantic similarity for the statistical analysis. Eighty German native speakers (mean age: 33.5 years; range: 18-70) took part in the pre-test

(20 ratings per item pair). They were presented with two members of a category at a time and were asked to use a six-point Likert scale (6 = very closely related; 1 = not at all related) to indicate their semantic similarity. Semantically similar items were defined as sharing many semantic features (e.g., *apricot* and *plum*: both are fruits, can be eaten, grown on trees, have a stone, are round …), while items with few or no shared features were defined as semantically distant (e.g., *apricot* and *telephone*). The results showed that the members of the 18 categories were overall perceived as closely related (mean: 4.64, *SD*: 1.31, range: 3.3 - 5.5). The 40 filler and practice items were semantically unrelated. All photographs were scaled to 3.5cm x 3.5cm and had a homogenous light grey background. Appendix A lists all materials used in this experiment.

We created eighteen different stimulus lists, in which the five members of each category were separated by 2, 4, 6 or 8 intervening items (lag value; Howard et al., 2006). The order in which categories appeared within a list and the order of the five members within each category were unique for each list. Care was taken to keep semantically related categories apart (e.g., land animals, marine animals, and insects), to avoid creation of superordinate categories. We also ensured that there were no more than five man-made or natural items in a row, to avoid any response bias in the classification task. Every participant was presented with three differently randomised versions of their list to investigate effects of repetition on semantic context effects.

2.1.3 Apparatus

The experiment took place in a noise-cancelling booth, with participants sitting approx. 30 cm from the microphone and approx. 80 cm from the screen. The pictures were presented on a 19" inch screen (1280x1024), using version 17.0 01.14.14 of the software Presentation® (Neurobehavioural Systems, Inc, www.neurobs.com) and naming latencies were registered by a voice-key (custom-made) and a Sennheiser MKH 416 P48 microphone.

2.1.5 Procedure

Prior to the main experiment, participants were familiarised with the materials. They were given sheets of paper with all photographs and the written names (random order) and were instructed to study each picture and its corresponding name. In the main experiment, participants first named 10 practice items before proceeding with their lists. At the start of each trial, a fixation cross was presented for 500 ms, followed by the picture. The picture remained on screen until a response was initiated, or for a maximum of 2500 ms. Starting with response onset, an inter-trial interval of 2000 ms with a blanc screen was initiated, before the next trial started. Participants were instructed to name the depicted objects as fast and as accurately as possible, using the label they had seen during the familiarisation phase.

2.2 Data acquisition and analyses

Behavioural response: Naming latencies were recorded automatically with a hardware voice-key from picture onset to speech onset, and the experimenter coded any voice-key or naming errors (incorrect responses, stuttering etc.). All statistical analyses were computed using R (R Development Core Team, 2017). Naming latencies were analysed for target trials only. Trials in which pictures were named incorrectly or dysfluently or in which the voice-key was triggered too late were excluded from the analysis (4.7%). To identify outliers, we combined light a-priori screening for artefactual responses with a removal of outliers that were not within normal distribution of the final model's residuals (for more details on this procedure, see Baayen & Milin, 2010). This resulted in the exclusion of 1% of the data a-priori (RT < 300 ms), while a further 1.8 % were excluded after model fitting (standardised residuals > than 2.5). As the reaction time data were not normally distributed, we used the Box–Cox procedure (Box & Cox, 1964) implemented in the boxcox-function in the package MASS (Venables & Ripley, 2002) to identify the most appropriate transformation. The inverse-transformed reaction times were fitted with a series of linear mixed effect models (LMM; Baayen et al., 2008), using the function lmer of the R package lme4 (Bates, Maechler, et al., 2015). *P*-values were computed with the lmerTest package (Kuznetsova et al., 2017). Models were initially run with a maximal random effect structure. To enable model convergence and avoid overfitting, we simplified the model by successively removing those random effects that explained the least variance, aiming to include the maximal random effect structure (using the rePCA function; see Bates, Kliegl, et al., 2015). The final model used for the main analysis included main fixed effects and a three-way interaction between the predictors Ordinal position (five ordinal positions of members within one category), Repetition (Repetition 0,1,2, i.e., three naming cycles with the same stimuli but different experimental lists) and Semantic similarity (for each item: mean values from semantic similarity rating), as well as two-way interactions between Ordinal position and Repetition and Ordinal position and Semantic similarity. The covariate Trial (consecutive trial number) was included to account for changes in the course of the experiment (i.e., trial-by-trial sequential effects, e.g., Alario & Moscoso del Prado Martin, 2010; Baayen & Milin, 2010; Riley et al., 2015). The random structure included random intercepts for Subjects, Semantic categories and Items nested within categories, by-subject random slopes for the interactions between Ordinal position and Repetition and between Ordinal position and Semantic similarity, as well as by-category random slopes for Ordinal position and the interaction between Ordinal position and Repetition (omitting all correlations to facilitate convergence). To test for a linear increase in reaction times between ordinal positions 1 and 5, we used polynomial contrasts (linear trend) for the predictor Ordinal position (for more details on contrast-coding, see Schad et al., 2020). The two predictors Repetition and Semantic similarity and the covariate Trial were centred and entered as continuous variables.

Electrophysiology: The continuous EEG was recorded at a sampling rate of 500Hz, using 62 Ag/AgCl electrodes arranged according to the extended 10/20 system. An external electrode near the lateral canthus of the left eye was used to measure electrooculograms. All electrode impedances were kept below 5kΩ and all electrodes were referenced to the left mastoid. The main experimental session was followed by a calibration procedure to obtain prototypical eye movements of each participant. These were required for the offline-removal of eye movements from the continuous EEG using the spatio-temporal dipole modelling procedure with the BESA software (Ille et al., 2002). Offline, the EEG was re-referenced using the average reference and then low-pass filtered (high cutoff at 30Hz, 24dB/oct). It was then segmented into epochs of 2100ms, starting 100ms before picture onset (baseline interval). The baseline interval was used for baseline-correction. Remaining artifacts were identified with an automatic artifact-rejection procedure, excluding segments with amplitude changes of more than 50 µV or an absolute amplitude of 200 µV.

As the continuous EEG was recorded during overt speech production, it was contaminated by articulation artifacts. To clean the EEG from these artifacts, we used the Residue Iteration Decomposition (RIDE) procedure (Ouyang et al., 2016), which decomposes ERPs into component clusters with distinct trial-to-trial variabilities (e.g., stimulus-locked, response-locked, and latency-variable component clusters). It identifies response-locked components (R component) containing the articulation artifacts based on their large amplitudes and highly variable trial-to-trial latencies and separates these from the stimulus-locked components (S components), which contain the actual brain responses to the stimulus (i.e., cleaned from speech artifacts, see Figure 1 in Appendix B).

In the analysis, we only included the S-component data of correct trials (in which the object was named correctly and within the time frame) that were not excluded due to excessive artifacts (i.e., 89.2% of the data). Based on previous research on ERP effects in continuous naming (e.g., Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017), we focused on posterior electrode sites (CP3, CP4, P5, P3, Pz, P4, P6, PO3, POz, PO4). In line with previous studies (e.g., Roelofs et al., 2016; Rose & Abdel Rahman, 2017), we averaged single-trial EEG data across these pre-selected electrodes for consecutive 50ms time windows, starting 100ms after picture onset until 650ms post picture onset. The averaged, single-trial data were then analysed using linear-mixed models for each of the 50ms time windows. First, each model analysed all three repetitions. In a second step, we used nested models for those time segments, where the main analysis revealed a significant interaction between the factors Ordinal position and Repetition to investigate effects of repetition in these time windows. As for the naming latencies, we aimed to include the maximal random effect structure for each model. Also, variable treatment was identical to that described in the analysis of the naming latencies. Our initial models included the covariates Trial and Semantic similarity. However, we excluded these variables from the final models, as they did not improve the fit of any of the models. The final models' fixed structure included main effects and a two-way interaction of Ordinal position and Repetition. The random structure included intercepts for the random factors Subjects, Semantic category and Items nested within categories, as well as by-subject random slopes for the factors Ordinal position, Repetition, and their interaction. For the three models analysing the time windows between 500 and 650, the above model structure let to overfitting and thus had to be slightly simplified by taking out the by-subject random slopes for Ordinal position and its interaction with Repetition. Finally, we calculated correlations for each of the 50ms time windows to test whether any observed ERP modulation is associated with the naming latencies. We correlated mean ERP amplitudes and mean RTs for the five ordinal positions in each time window, averaging across all participants (for a similar approach, see e.g., Costa et al., 2009; Rabovsky et al., 2021; Rose & Abdel Rahman, 2017)

2.3 Results

Naming latencies: Table 1 contains the results of the main LMM analysis. In the course of the experiment, participants' overall naming latencies increased (main effect Trial). Furthermore, overall naming latencies were significantly influenced by repetition, decreasing from one repetition to the next (main effect Repetition). Within a given semantic category, however, participants' naming latencies increased on average by 18ms from one category member to the next (main effect Ordinal position), revealing the predicted cumulative semantic interference (Figure 1, left). Furthermore, we found a significant interaction of Ordinal position and Repetition. A nested version of the same model revealed that the magnitude of the CSI effect significantly decreased from Repetition 0 to Repetition 1 ($b = -0.05$, $SE = 0.01$, $t = -3.27$, $p < 0.01$) but not from Repetition 1 to Repetition 2 ($b = -0.006$, $SE = 0.01$, $t = 0.46$, $p = 0.65$, see Figure 1, right). Nonetheless, separate analyses for the three repetitions showed that strong interference was present in all of them (Repetition 0: $b = 0.089$, $SE = 0.01$, $t = 7.37$, $p < 0.001$ (129ms); Repetition 1: $b = 0.053$, $SE = 0.01$, $t = 5.02$, $p < 0.001$ (34ms); Repetition 2: $b = 0.056$, $SE = 0.01$, $t = 5.05$, $p < 0.001$ (53ms)). While there was no main effect for semantic similarity, the results showed that it significantly influenced the observed CSI effect in all repetitions (interaction of Ordinal position and Semantic similarity; no three-way interaction with Repetition), with more closely related category members inducing stronger interference than more loosely related ones.

Table 1. Results of the LMM-analysis of behavioural data collected in Experiment 1.
Model: -1000/RT ~ Ordinal position* Repetition +Ordinal position*Semantic similarity+Ordinal position: Repetition:Semantic similarity+ Trial +(Ordinal position * Repetition + Ordinal position * Semantic similarity ||subject) + (1| Category/Item) + (0+ Ordinal position + Ordinal position: Repetition ||Category)

	-1000/RT			
Predictors	*Estimates*	*std. Error*	*t-value*	*p*
(Intercept)	-1.18	0.03	-43.43	**<0.001**
Ordinal position	0.07	0.01	9.81	**<0.001**
Repetition	-0.10	0.01	-9.92	**<0.001**
Semantic similarity	<0.01	0.03	0.19	0.853
Trial	< 0.01	<0.01	2.79	**0.005**
Ordinal position: Repetition	-0.02	0.01	-2.32	**0.033**
Ordinal position: Semantic similarity	0.04	0.01	2.83	**0.010**
Ordinal position: Repetition: Semantic similarity	-0.01	0.02	-0.52	0.604

Random Effects

	Variance	**Sd**
Subjects (Intercept)	0.01	0.10
Subjects (Repetition)	< 0.01	0.03
Subjects (Ordinal position : Repetition)	< 0.01	0.02
Subjects(Ordinal position)	< 0.01	0.02
Subjects (Ordinal position : Semantic similarity)	< 0.01	0.03
Subjects(Semantic similarity)	< 0.01	0.04
Category (Intercept)	<0.01	0.07
Category (Ordinal position)	<0.01	<0.01
Category (Ordinal position: Repetition)	<0.01	0.02
Category \Item (Intercept)	0.01	0.12
Residuals	0.05	0.23

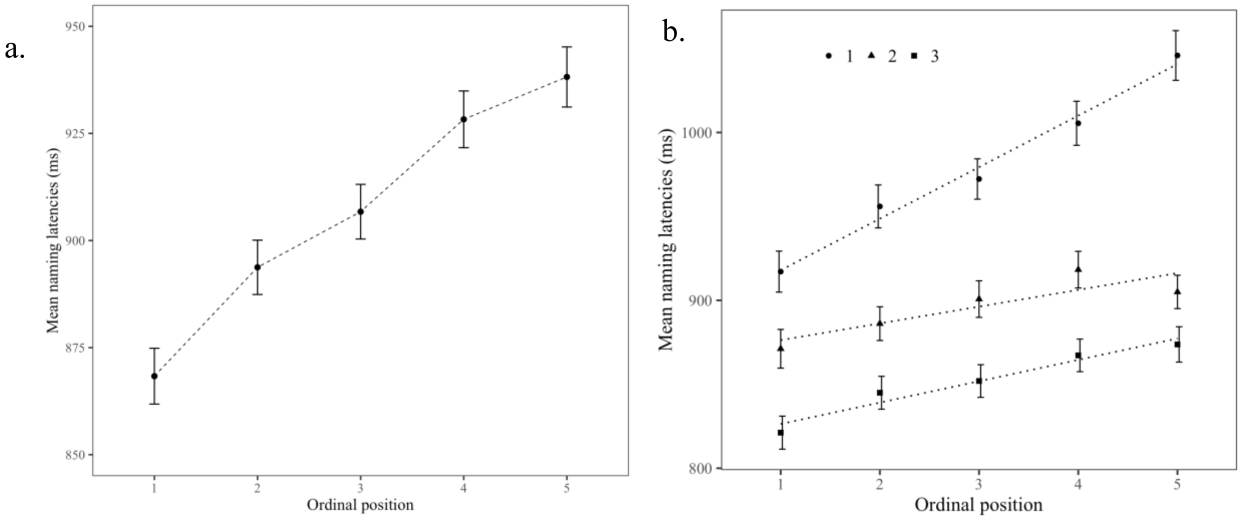


Figure 1: Mean naming latencies with error bars (in milliseconds) per Ordinal position (Figure 1a, left), broken down by Repetition (Figure 1b, right)

Electrophysiology: Table 2 shows the results of the LMMs for each of the 50ms intervals (over all repetitions) and Table 3 those of the corresponding nested models. The results revealed two effect clusters in the main analysis: From 250 to 400ms, mean amplitudes linearly increased from one ordinal position to the next (main effects of Ordinal position), indicating the characteristic posterior positivity (Figure 2). The effect was affected by repetition (interaction Ordinal position and Repetition). The nested models (Table 3) showed that the duration of the posterior positivity decreased by repetition, as it was present from 250 to 450ms in Repetition 0, from 250 to 350ms in Repetition 1 but only from 250-300ms in Repetition 3 (see Figure 2 in Appendix B for ERPs and topographies for each repetition). The second effect cluster in the main analysis started at 450ms post picture onset and lasted until about 600ms. Here, mean amplitudes of the posterior electrodes linearly decreased as a function of Ordinal position (main effect Ordinal position in Table 2), indicating a posterior negativity (Figure 2). The onset of this effect differed for the three repetitions (interaction between Ordinal position and Repetition for the time windows 400-450ms and 450-500ms:). The nested models for these two time windows revealed that the length of the posterior negativity increased with each repetition (Rep 0: 500-600ms, Rep1: 450-600ms, Rep2: 400-600ms). The correlation analyses revealed that both effect clusters were correlated with reaction time (see column *rho* in Table 2). The posterior positivity was positively correlated with RT from 300 to 350ms when analysing all repetitions together. Given the strong influence of repetition on the posterior positivity, we also conducted separate correlation analyses for each repetition (see column *rho* in Table 3). These revealed that the posterior positivity in Repetition 0 was positively correlated with RT from 300 to 450ms ($r = 0.89$, p<0.05). The posterior negativity was negatively correlated with RT in all repetitions from 450 to 550ms in ($r = -0.95$, $p < 0.05$).

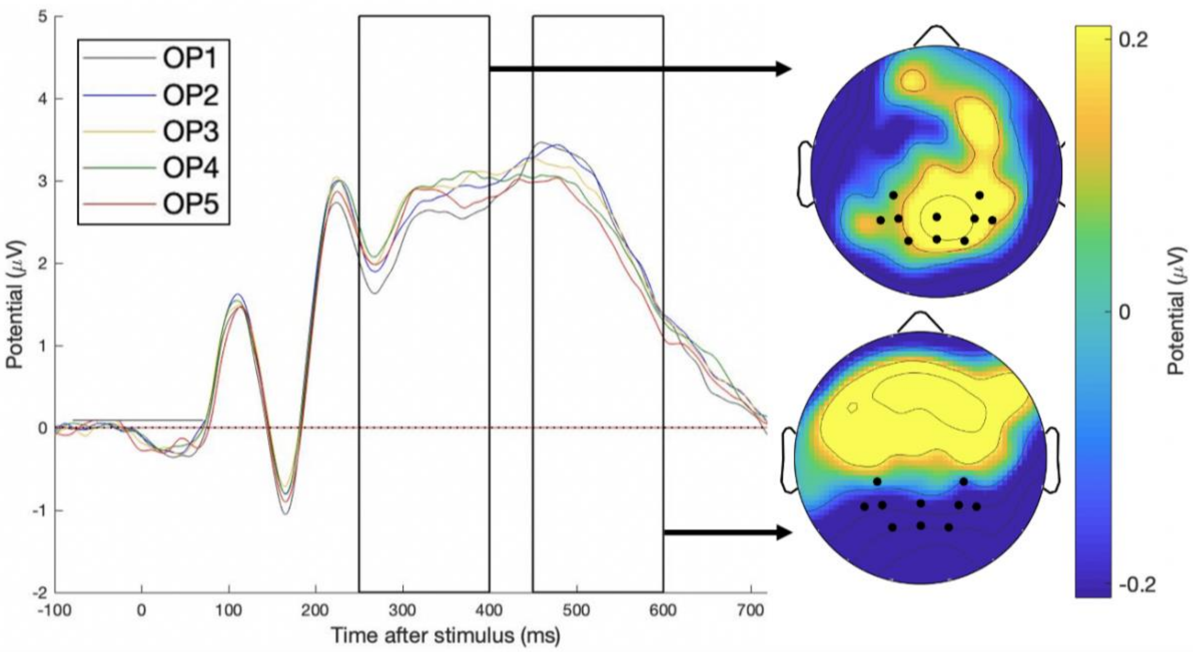
Table 2: LMM-results for the factors Ordinal position and Repetition at posterior electrode sites for each of the 50ms time windows. Spearman's rank correlation coefficient (rho) indicates the correlation between mean amplitudes and reaction times for each time window.

	Ordinal position			**Repetition**		**Ordinal position x Repetition**	
Time window	***t***	***p***	***rho***	***t***	***p***	***t***	***p***
100-150 ms	ns			2.02	0.05	ns	
150-200 ms	ns			ns		ns	
200-250 ms	ns			ns		ns	
250-300 ms	2.66	0.01	n.s.	2.82	< 0.01	-1.85	0.07
300-350 ms	3.10	< 0.01	0.88	2.76	< 0.01	-3.23	<0.01
350-400 ms	1.83	0.08	n.s.	4.03	<0.01	-2.93	<0.01
400-450 ms	ns			5.68	< 0.01	-2.95	0.01
450-500 ms	-2.92	0.02	-0.95	3.86	<0.01	-2.37	0.02
500-550 ms	-3.27	<0.01	-0.95	ns		ns	
550-600 ms	-1.74	0.08	n.s.	-2.88	<0.01	ns	

Note: Included electrodes: CP3, CP4, P5, P3, Pz, P4, P6, PO3, POz, PO4

Table 3: Results of nested models (for each repetition) at posterior sites. Spearman's rank correlation coefficient (rho) indicates the correlation between mean amplitudes and reaction times for each time window.

	Repetition 0			**Repetition 1**			**Repetition 2**		
Time window	***t***	***p***	***rho***	***t***	***p***	***rho***	***t***	***p***	***rho***
300-350	3.95	<0.001	0.89	2.13	0.03	n.s.	ns		
350-400	3.60	<0.001	0.89	n.s.			n.s.		
400-450	2.57	0.01	0.89	ns			-1.90	0.06	n.s.
450-500	ns			-2.30	0.03	-0.87	-3.16	<0.01	-0.88



Figures 2. ERPs at posterior electrodes for Experiment 1 (all repetitions pooled) with corresponding topographies for significant effects. For the ERPs, all electrodes of interest were pooled. The two significant effects are captured within the black boxes and are depicted in the topographies) (above: 250-400 ms [posterior positivity]; below: 450-600 ms [posterior negativity]). These show the difference between Ordinal position 5 and 1 (i.e., the last minus the first category members).

2.4 Discussion Experiment 1

In Experiment 1, we observed the expected cumulative interference effect in the behavioural as well as in the electrophysiological data. Behaviourally, the effect was evidenced by a linear increase of participants' naming latencies with each additionally named category member (e.g., Howard et al., 2006). This CSI effect was modulated by two factors, namely Semantic similarity and Repetition. In line with previous research, cumulative interference in naming times was stronger for items that were semantically closely related than for more distantly related ones (Döring et al., 2022b, 2022a; Rose & Abdel Rahman, 2017). Additionally, the effect was negatively influenced by repetition. While cumulative interference was present in all three repetitions, the effect decreased significantly with the first repetition (from Repetition 0 to Repetition 1). This supports recent findings from our own lab (Döring et al., 2022b; Holtz et al., n.d.) but is not in line with other studies reporting cumulative interference independent of repetitions (Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Navarrete et al., 2010; Rose & Abdel Rahman, 2017). We will discuss this point further in the General discussion.

In the main ERP analysis, we observed the two components that had previously been linked to cumulative interference, namely a posterior positivity between 250ms and 400ms, and a posterior negativity between 450ms and 600ms (see Figure 2). Both components systematically increased with each named category member, replicating results of previous studies (Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017, but see Llorens et al., 2014). We found both effects to be correlated with reaction times. In line with others, we assume that the early positivity at posterior sites is an indicator for lexical access and that the systematically increasing positivity within semantic categories reflects an increasing difficulty to select the target from among a group of coactivated lexical entries (Costa et al., 2009; Rose & Abdel Rahman, 2017). While previous studies have not reported an influence of repetition on this ERP component (Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017), our results paint a different picture. We find that the effect's duration systematically decreases with each repetition (Rep 0: 200ms, Rep 1: 100ms, Rep 2: 50ms) and that the positive correlation with the behavioural CSI effect was solely driven by the first naming instance (Repetition 0) but not the two repetitions. This reduction of neural responses to repeated stimuli has been reported in other studies (e.g., Gruber & Müller, 2005). These results thus mirror the behavioural data, where we also observed a systematic decrease of the CSI effect. The second neural effect we observed was a negative modulation between 450 to 600ms, which was negatively correlated with reaction times (see also Rose & Abdel Rahman, 2017). This posterior negativity was also strongly influenced by repetition, as its duration increased with each repetition (Rep 0: 50ms; Rep1: 150ms; Rep2: 200ms). This component has been tentatively linked to the learning mechanism responsible for cumulative interference (Rose & Abdel Rahman, 2017). We will discuss the function of ERPs and their interaction with repetition further in the General discussion.

3. Experiment 2: Continuous classification

The second experiment was conducted to investigate cumulative facilitation (Belke, 2013) and to better understand its commonalities and differences with cumulative interference. Experiment 2 used a non-verbal semantic classification task with identical picture stimuli as in Experiment 1. The same participants as in Experiment 1 were instructed to classify the presented picture as either man-made or natural and to indicate their decision via button-press. In our behavioural data, we expected to replicate cumulative facilitation found in previous studies (Belke, 2013; Döring et al., 2022a; Riley et al., 2015). For the EEG data, we hypothesised a reduced N400 as a function of Ordinal position, reflecting increased ease to access semantic information. If, however, the late negativity linked to cumulative interference reflects the learning mechanism responsible for the longevity of the effect, we additionally expected an increased negativity in a similar time window as in Experiment 1. As in Experiment 1, we investigate interactions between Repetition and Ordinal Position.

3.1 Participants, materials, apparatus, experimental design

Participants, materials, apparatus and experimental lists were identical to those in Experiment 1. Every participant first completed Experiment 1. After a break of approx. 15 to 20 minutes, they continued with Experiment 2. When choosing the experimental items for Experiment 1 and 2, care was taken that they included an equal number of natural and man-made entities. Also, the experimental lists contained no more than five man-made or natural items in a row, to avoid an answering bias in the classification task. Again, each participant was presented with three experimental lists to investigate effects of item repetition on cumulative facilitation.

3.2 Procedure

At the start of each trial, a fixation cross was presented for 500ms, followed by the picture. The picture was presented until a manual response was given, or for a maximum of 2500 ms. After an inter-trial interval of 2 seconds, the next trial started. Participants were instructed to indicate via button-press whether the depicted objects were natural or man-made. Reaction times were recorded from picture onset and automatically registered. Incorrect responses were automatically coded. The button classification (i.e., left button = man-made, right button = natural) alternated between participants.

3.3 Data acquisition and analyses

Reaction times: The data analysis (software, packages, contrast-coding, data transformation and model selection procedure) was identical to Experiment 1, with two exceptions. First, outliers were defined as reaction times shorter than 250ms and longer than 2000ms. Second, based on previous studies (Belke, 2013; Döring et al., 2022a; Riley et al., 2015), the initial (i.e., maximal) model used to analyse the data also included Classification type (man-made vs. natural) as an additional fixed factor to account for differences between the two classification types. As this factor did not improve model fit, it was excluded from the final model.

As in Experiment 1, we excluded incorrect trials (6%) and those which were identified as outliers (0.2%) from the analysis. Of the remaining data, a further 1.74% were excluded after fitting the linear-mixed model. The final model used for the analysis included Ordinal position (five ordinal positions of category members), Repetition (Repetition 0,1,2, first classification cycle and 2 repetitions) and Semantic similarity (values from semantic similarity rating, see section on Material) as fixed effects as well as their two- and three-way interactions. Trial number (consecutive trial number) was included as a covariate. The random effect structure consisted of intercepts for the random factors Subject, and Item nested under Semantic category as well as by-subject and by-category random slopes for Repetition.

Electrophysiology: The data acquisition and analysis procedure of the continuous EEG was identical to Experiment 1, except that the removal of articulation artifacts was not necessary here. Again, only the data of correct trials and those without excessive artifacts were included (89.2 %). Our ROI consisted of the same posterior electrodes we tested in Experiment 1 (CP3, CP4, P5, P3, Pz, P4, P6, PO3, POz, PO4). This allowed us to test for our two hypotheses, namely a reduced N400 reflecting semantic priming, and the posterior negativity reported in continuous naming, which has been tentatively linked to the learning mechanism responsible for cumulative interference. As in Experiment 1, we averaged single-trial EEG data across these pre-selected electrodes for consecutive 50ms time windows, starting 100ms after picture onset until 600ms post picture onset. The averaged, single-trial data were then analysed using linear-mixed models for each of the 50ms time windows. In a first step, we analysed the data of all repetitions together. As we were also interested in the influence of repetition on cumulative facilitation, we next used nested models for those time windows in which the main analysis revealed a significant interaction between Ordinal position and Repetition. Again, we aimed to include the maximal random effect structure for each model and variable treatment was identical to that described above. As in Experiment 1, our initial model included the covariates Semantic similarity and Trial number. As these variables did not improve model fit, we excluded them from all EEG analyses. The final models' fixed structure included main effects and a two-way interaction of Ordinal position and Repetition. The random structure included intercept for the random factors Subject and Item, as well as by-subject random slopes for the factor Repetition.

Additional analysis: An additional analysis tested whether behavioural cumulative interference can be used to predict behavioural cumulative facilitation, an attempt to replicate the results from our previous study (Döring et al., 2022a). As in Döring et al. (2022a), we first determined both context effects by calculating the reaction time difference (in ms) between the first and the last category member (Ordinal position 1 and 5) for each subject, category and repetition for each task. Categories for which either effect could not be calculated due to missing trials were excluded from the analysis (19%). The facilitation effect was log-transformed and used as dependent variable in a linear-mixed model, while the interference effect was centred and entered as a fixed factor. The fixed structure also included the factor Repetition and Semantic similarity, as well as two-and three-ways interaction of the fixed factors. The random structure only included by-subject random slopes for the factor Repetition. This best-fitting model was identified through model comparisons, following the same procedure described for Experiment 1.

3.4 Results

Response latencies:

Table 4 contains the results of the linear-mixed model analysis of the behavioural data. As depicted in Figure 3a, response latencies linearly decreased on average by 33 ms within semantic categories (main effect Ordinal position), reflecting cumulative facilitation. This effect was modulated by Repetition (interaction Ordinal position: Repetition) but not by Semantic similarity (no interaction of Ordinal position and Semantic similarity and no three-way interaction with Repetition). Separate post-hoc analyses of each of the three repetitions revealed that the linear cumulative facilitation effect was strongly present in Repetition 0 (*b*= -0.11, *SE* = 0.016, *t* = -7.10, *p* <0.001) and more weakly in Repetition 2 (*b*= -0.05, *SE* = 0.016, *t* = -2.91, *p* = 0.006) but not at all in Repetition 1 (*b* = 0.006, *SE* = 0.015, *t* = 0.43, *p* = 0.67), as depicted in Figure 3b. A follow-up analysis for Repetition 1 showed a significant quadratic effect (*b* = 0.029, *SE* = 0.014, *t* = 2.07, *p* = 0.034), indicating that the response latencies initially decreased (from Ordinal position 1 to 3) but then increased again (Ordinal position 3 to 5). Overall, participants' response latencies decreased with each repetition (main effect Repetition) and throughout the experiment (main effect Trial number).

Table 4: Results of the LMM analysis of behavioural data collected in Experiment 2.
Model: -1000/RT ~ Ordinal position* Repetition +Ordinal position*Semantic similarity+Ordinal position: Repetition:Semantic similarity+ Trial +(Repetition ||Subject) + (1| Category/Item) + (0+ Repetition ||Category)

	-1000/RT			
Predictors	*Estimates*	*std. Error*	*t-value*	*p*
(Intercept)	-1.78	0.05	-35.53	**<0.001**
Ordinal position	-0.05	0.01	-5.81	**<0.001**
Repetition	-0.16	0.02	-7.46	**<0.001**
Semantic similarity	-0.01	0.02	-0.31	0.754
Trial	-0.00	0.00	-2.42	**0.015**
Ordinal position* Repetition	0.04	0.01	4.28	**<0.001**
Ordinal position* Semantic similarity	0.01	0.02	0.68	0.499
Ordinal position*Repetition* Semantic similarity	-0.01	0.02	-0.54	0.592
Random Effects				
σ^2	0.12			
$\tau_{00\ \text{item.cat}}$	0.00			
$\tau_{00\ \text{subject}}$	0.01			
$\tau_{00\ \text{subject.1}}$	0.07			
$\tau_{00\ \text{cat}}$	0.00			
$\tau_{00\ \text{cat.1}}$	0.01			
$\text{ICC}_{\text{item.cat}}$	0.02			

$\text{ICC}_{\text{subject}}$	0.04
$\text{ICC}_{\text{subject.1}}$	0.34
ICC_{cat}	0.00
$\text{ICC}_{\text{cat.1}}$	0.03

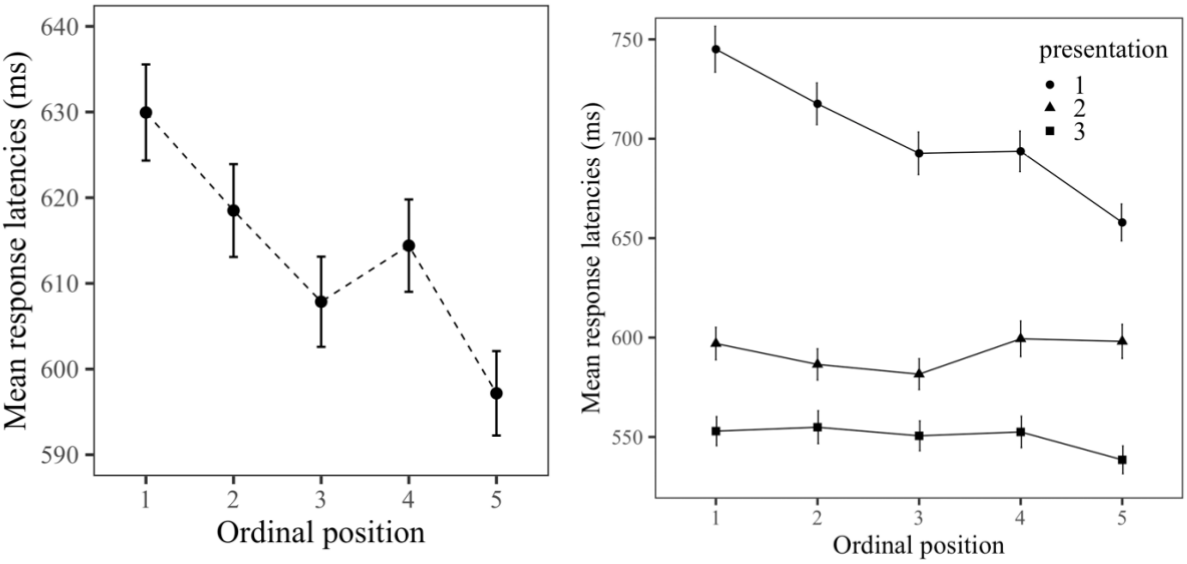


Figure 3. Experiment 2: Mean response latencies with error bars (in milliseconds) per Ordinal position (Fig 3a, left), broken down by Repetition (Fig 3b, right).

Electrophysiology: Table 5 contains the results of the LMM-analyses of the pre-defined ROI at posterior electrode sites. Overall, the results revealed three significant ERP effects. First, negative amplitudes increased as a function of Ordinal position between 100 and 250ms after picture onset (Table 5, Figure 4). There was no interaction between Ordinal position and Repetition in this time window (see Figure 3 in Appendix B for topographies and ERPs for each repetition). Secondly, we found a significant interaction of Ordinal position and Repetition between 350 and 400ms. The nested model revealed a positive modulation within this time window in Repetition 0 (b = 0.30, SE = 0.14, t = 2.11, p = 0.04), that is, mean amplitudes systematically increased as a function of previously classified category members (i.e., Ordinal position, Figure 5). There was no such positive modulation in Repetition 1 or 2 (both p > 0.1)[2]. The third effect was a linear decrease in amplitudes within semantic

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[2] In addition to these planned analyses, we conducted one post-hoc analysis (data driven, based on visual inspection) at left temporal electrode sites for Repetition 1 and 2 at the typical N400 window (300-500ms). Visual inspection of the topographies of these repetitions suggested a positive modulation at that location. As N400 modulations have also been reported at left temporal sites in the literature (e.g., Geukes et al., 2013), we decided

categories from 450 to 600ms (Table 5, Figure 4). This negative modulation was not significantly influenced by repetition (no interaction Ordinal position and Repetition in any of these time windows). Like in Experiment 1, we conducted correlation analyses for each 50ms time window to investigate whether the ERP modulations are correlated with the reaction times. We found no significant correlations between RTs and the early negativity observed between 100 and 250ms (all $p > 0.05$) and no correlation between the positive modulation observed between 350 and 400ms in Repetition 0 ($p > 0.05$). However, the late negativity was positively correlated with RT from 500 to 600ms post picture onset (r = [0.89-0.96], $p < 0.05$).

Table 5: LMM-results for the factors Ordinal position and Repetition at posterior ROI (all repetitions pooled).

	Ordinal position			**Repetition**		**Ordinal position x Repetition**	
Time window	***t***	***p***	***rho***	***t***	***p***	***t***	***p***
100-150 ms	-2.78	<0.01	n.s.	n.s.		n.s.	
150-200 ms	-2.01	0.05	n.s.	n.s.		n.s.	
200-250 ms	-2.09	0.04	n.s.	n.s.		n.s.	
250-300 ms	n.s.			-1.72	0.09	n.s.	
300-350 ms	n.s.			-2.00	0.05	n.s.	
350-400 ms	n.s.			-2.58	<0.001	-2.75	<0.01
400-450 ms	n.s.			-4.38	<0.001	n.s.	
450-500 ms	-2.21	0.03	n.s.	-6.01	<0.001	n.s.	
500-550 ms	-3.53	<0.001	0.89	-6.78	<0.001	n.s.	
550-600 ms	-3.41	<0.001	0.96	-6.61	<0.001	n.s.	

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to analyse this ROI. The left temporal ROI included six electrodes (T7, C5, TP7, CP5, P7, P5), based on the effect reported in Geukes et al. (2013). The analyses of the 50ms time windows revealed a positive modulation from 300 to 400ms in Repetition 2 (300-350: $t = 3.12$, $p < 0.01$; 350-400: $t = 1.93$, $p = 0.05$), meaning amplitudes increased linearly from one category member to the next (Figure 4, Appendix B). In Repetition 1, we only observed a marginal increase of amplitudes between 300 and 350ms at left temporal electrode sites ($t= 1.84$, $p = 0.07$). The correlation analysis showed no significant correlation between these positive modulations and RTs (all $p > 0.05$; see Table 2 in Appendix B). As this analysis was not planned and adds to the already complex data reported in this article, we decided not to report it in the main text and will not discuss it further. Yet, some readers might find the information insightful.

Table 6: LMM-results of the nested model (for repetition) in the 350-400ms time window.

	Repetition 0			Repetition 1		Repetition 2	
Time window	***t***	***p***	***rho***	***t***	***p***	***t***	***p***
350 - 400 ms	2.11	0.04	ns	n.s.		n.s.	

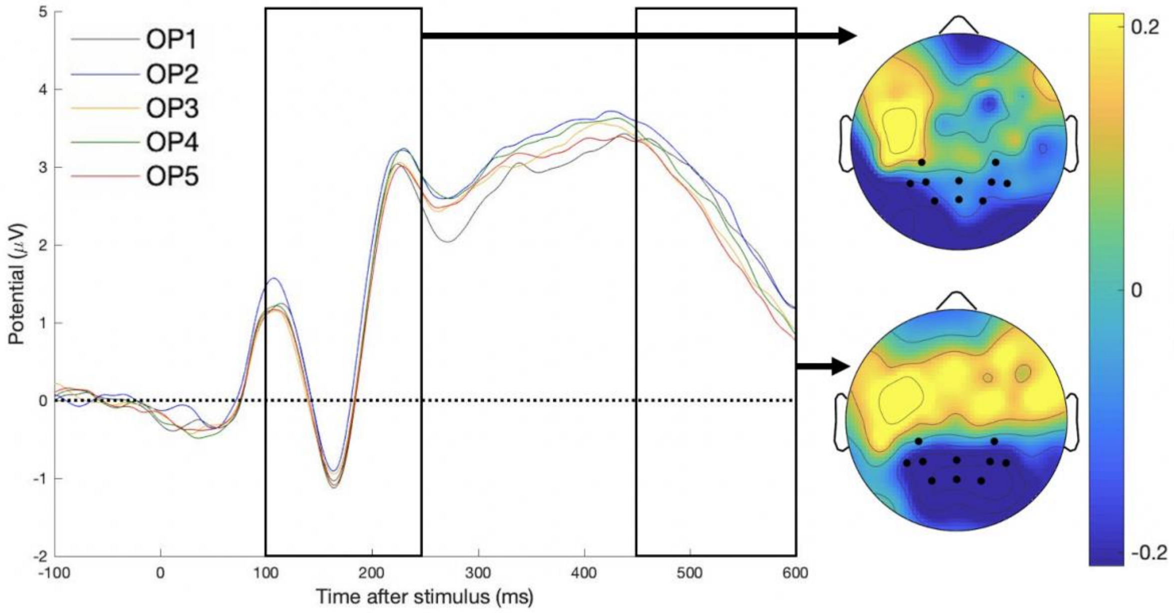

Figure 4. Experiment 2: ERPs at posterior electrodes with corresponding topographies for significant effects. All repetitions were pooled. For the ERP, the electrodes of interest at posterior sites were pooled. The black boxes indicate significant linear effects. The topographies depict time windows of significant effects (top: increasing early negativity, 100 – 250 ms; bottom: increasing late negativity, 450-600 ms post-picture onset).

Note: The topographies show the difference between Ordinal position 5 and 1 (i.e., the last minus the first category members)

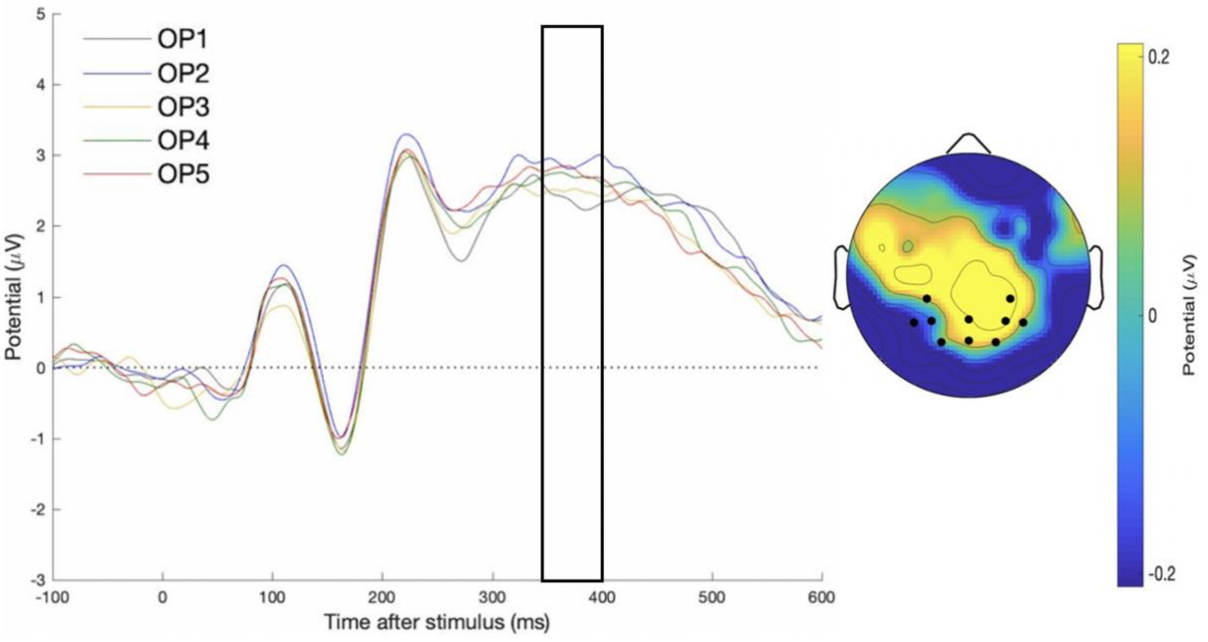

Figure 5: Topography and ERP of increasing positivity in the N400 window (350-400ms) at posterior sites in Repetition 0. For the ERP, all electrodes of interest at posterior sites were pooled. The black box indicates the significant linear modulation depicted in the topography. Topography shows the difference between Ordinal position 5 and 1 (i.e., the last minus the first category members).

Joint analysis of data from Experiment 1 and 2: Table 1 in Appendix B contains the results of the additional analysis in which the behavioural interference effect (Experiment 1) was used as a predictor for the behavioural facilitation effect (Experiment 2). The results show a significant main effect for the factor Interference effect (t = 2.68, p = 0.007), with weaker interference predicting stronger facilitation (Figure 5 in Appendix B). This effect was neither modulated by Repetition (interaction Interference effect * Repetition: t = 0.62, p = 0.53) nor by Semantic similarity (interaction Interference effect * Semantic similarity: t = -0.45, p = 0.65) or by an interaction of these factors (interaction Interference effect * Repetition * Semantic similarity: t = -0.26, p = 0.79). As a post-hoc analysis, we ran the same analysis for the ERP data. Here, we selected the time window between 450 and 550 ms post picture onset for the analysis, as we observed a significant posterior negativity in this time window in both tasks. As for behavioural data, we first calculated the mean amplitudes of ordinal position 1 and 5 for each subject, category and repetition, before calculating the amplitude difference between the two. We then ran a linear mixed model, including the ERP-effect of Experiment 2 as the dependent and the ERP-effect of Experiment 1 as the independent variable, as well as Repetition as an additional fixed factor. The results show no significant effect for the ERP amplitudes of the naming task (t = 0.5, p = 0.6).

3.5 Discussion Experiment 2

We obtained the expected cumulative facilitation effect in the behavioural data, reflected by a linear decrease of response times within semantic categories (Belke, 2013; Riley et al., 2015). Furthermore, we replicated our previous findings that cumulative facilitation is influenced by repetition (Döring et al., 2022a). We found strong facilitation in the first presentation (Repetition 0) (about 22ms from one category member to the next) and weak facilitation in the third presentation (Repetition 2) (about 4ms from one category member to the next). The second presentation (Repetition 1) showed no linear facilitation effect, and a post-hoc analysis revealed a quadratic effect. Meanwhile, cumulative facilitation was not modulated by semantic similarity, in line with results from our previous study (Döring et al., 2022a)[3].

In the electrophysiological data, we observed three effects: First, a posterior negativity from 100 to about 250ms. Second, a positivity at posterior sites between 350 and 400ms in Repetition 0. Third, a posterior negativity between 450 and 600ms that was not influenced by repetition. The spatial distribution and the polarity of the positive effect from 350-400ms in Repetition 0 is comparable to those observed in other semantic priming studies (semantic categorisation/judgement: Geukes et al., 2013; McPherson & Holcomb, 1999; speech production: Blackford et al., 2012; Lorenz et al., 2021). Thus, we interpret the positivity as a reduced N400, which we hypothesised would reflect cumulative facilitation in the electrophysiological data. We will discuss this ERP component further in the General discussion.

For the late negativity from 450 to 600ms, amplitudes systematically decreased within semantic categories and its temporal properties and topographical distribution is similar to the negativity observed in Experiment 1. As mentioned earlier, this posterior negativity could reflect the learning

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[3] In fact, in the previous study, we found semantic similarity to influence cumulative facilitation after 3 runs, namely in Repetition 3 and 4 (Döring et al., 2022a).

mechanism responsible for cumulative interference. Based on this and the assumption that continuous interference and facilitation are functionally linked, we hypothesised that we might find a similar negative component in the classification task. We will discuss the function of this component further in the General discussion.

The earliest modulation found in the classification task was a negativity at posterior sites from 100-250ms. Previous research has taken components at this early time window (P1, N1) to reflect low and high-level visual perceptual processing during object recognition, or an early interaction between perceptual and semantic processing (Abdel Rahman & Sommer, 2008; Eddy & Holcomb, 2010; Eddy et al., 2007; Itier & Taylor, 2004; Lin et al., 2021). Thus, the observed modulation might reflect a reduced effort to identify objects due to priming of perceptual/semantic features by previously classified category members.

The joint analysis of the behavioural data from Experiment 1 and 2 showed that cumulative interference found in Experiment 1 can be used to predict cumulative facilitation in Experiment 2. This replicates results from our previous study (Döring et al., 2022a) and corroborates a previous finding that cumulative interference and facilitation can influence one another when picture naming and picture classification alternate within the same experiment (Belke, 2013). Our result thus provides additional evidence that cumulative interference and cumulative facilitation are functionally linked, with a shared origin at the conceptual level. The direction of the prediction, namely strong interference predicting weak facilitation perfectly replicates the results from our previous study (Döring et al., 2022a). While this result might seem surprising at first, the order of the two tasks might explain the direction. In the naming task, fine-grained, deep processing of all semantic features of a target, particularly unique features that it does not share with other category members, is necessary to perform the task (i.e., to select one specific target from among coactivated competitors). After successfully naming a target, the links between the features and the target's lexical representation would be strengthened. The strengthening of the unique features would then attenuate the facilitation effect in the following classification task, as this is based on shared features of the category members (for a more detailed explanation (Döring et al., 2022a). This explanation is based on previous findings that also showed an attenuated facilitation effect after successful naming targets (Belke, 2013, Exp. 5). The post-hoc analysis of the EEG data revealed no such effect, that is, the posterior negativity from Experiment 1 between 450 and 550ms post picture onset could not be used as a predictor for the posterior negativity from Experiment 2 in the same time window. We will discuss this point further in the General discussion.

4. General discussion

We investigated cumulative interference in continuous picture naming and cumulative facilitation in continuous classification with behavioural and electrophysiological measures, to gain a comprehensive understanding of the commonalities and difference between the two context effects. There was clear evidence for both context effects in the behavioural as well as the electrophysiological data. In the following, we first discuss the context effects separately before comparing the two.

Cumulative interference: In continuous picture naming, we observed cumulative interference as the typical increase in naming latencies within semantic categories. Like many others, we assume that this slowing reflects the participants' increased difficulty to select the lexical representation of the target from among the co-activated category members (Abdel Rahman & Melinger, 2019; Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010; Roelofs, 2018). Cumulative interference in naming latencies was influenced by repeated presentation of the pictures, which was not reported in most earlier studies (e.g., Costa et al., 2009; Kuhlen & Rahman, 2021; Navarrete et al., 2010; Rose & Abdel Rahman, 2017). While CSI was present in all three repetitions, its magnitude decreased after the first naming instance. Note that we found a similar interaction in our previous study with noun-noun compound targets (Döring et al., 2022b) and a meta-analysis on semantic interference in social settings also revealed strong repetition effects on cumulative interference (Holtz et al., n.d.). Furthermore, a closer look at some of the other studies' descriptive data suggests that the cumulative interference might not be as consistent across repetitions as previously assumed (e.g., Navarrete et al., 2010, p. 282: Repetition 0: 74ms, Repetition 1: 57ms, Repetition 2: 54ms, Repetition 3: 44ms; Rose & Abdel

Rahman, 2017: Repetition 0: 52ms, Repetition 1: 50ms, Repetition 2: 36ms[4]). More importantly, a reanalysis of the data from Rose and Abdel Rahman (2017) using a linear mixed model reveals a significant influence of repetition on the interference effect (interaction Ordinal position * Repetition: $b = -0.01$, $SE = 0.005$, $t = -1.990$, $p = 0.047$, see Table 3 in Appendix B for the full model output). Presumably, the more flexible and robust LMMs are more suitable to detect interactions with repetition than the repeated-measures ANOVAs used by these studies (Baayen et al., 2008). However, we found no significant influence of repetition on cumulative interference in a previous study, in which we did analyse the data with LMMs (Döring et al., 2022a)[5]. One important factor might be the way in which the familiarisation phase was conducted. While participants in the current study simply studied the pictures and the corresponding names on sheets of paper, participants in our previous study (Döring et al., 2022a) saw the stimuli in a random order on screen and were instructed to overtly name the depicted objects[6]. The first naming instance in this study was therefore during familiarisation, which was neither recorded nor analysed. Consequently, the reported first naming instance was actually the second, and it is thus possible that interference decreased from the first naming instance to the next. Taken together, the results suggest that cumulative interference can be observed behaviourally even after multiple repetitions, but that its magnitude decreases when repeatedly naming the same items. Future studies using cumulative interference as a tool might want to take this into consideration. These behavioural repetition effects are supported by the electrophysiological data.

In the EEG data of the continuous naming task, we observed a posterior positivity between around 250 and 400ms, followed by a posterior negativity from around 450 to 600ms, replicating previous studies (Costa et al., 2009; Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017; but

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[4] Rose and Abdel Rahman (2017) did not report the descriptive data in their publication. The information was obtained when reanalysing their data.

[5] Please note that we did find a significant influence of repetition on the interaction between Lag and Ordinal position in our previous study (Döring et al., 2022a). We observed weaker interference in long-lag runs (6 or 8 intervening items) compared to short-lag runs (2-4 intervening items) but only after several naming instances.

[6] The familiarisation phase in our previous study was conducted in that manner to ensure participants did not make an excessive number of mistakes on the morphologically complex target words (noun-noun compounds, e.g., apple tree, canopy bed, index finger).

see LLorens et al., 2014). We found both components to be correlated with reaction times. This provides corroborating evidence that both components are part of the neurocognitive signature of cumulative interference in picture naming (Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017). We interpret the earlier positivity as an index for lexical access (see also Costa et al., 2009; Kuhlen & Rahman, 2021; Rose & Abdel Rahman, 2017). Its onset is in line with other speech production studies that investigated the time course of lexical retrieval (Aristei et al., 2011; Bürki, 2017; Llorens et al., 2014) and roughly corresponds to the onset of lexical selection estimated in meta-analyses (Indefrey & Levelt, 2004; Indefrey, 2011). The increasing positivity with each named category member thus likely reflects the increased difficulty to select the lexical entry of the target word, behaviourally reflected by longer naming latencies. This is supported by the positive correlation between the posterior positivity and reaction times (see also Costa et al., 2009; Rose & Abdel Rahman, 2017). The function of the second component, namely the posterior negativity, is less clear. As we find the same component in Experiment 2, we will discuss its function below, when comparing the two context effects.

Contrary to previous continuous picture naming studies, we observed a strong influence of repetition on both ERP components. The strength of the posterior positivity decreased with repetitions (the duration as well as the size (estimates) of the ERP component). This mirrors the behavioural CSI effect and thus clearly shows that cumulative interference is vulnerable to repetition. An obvious explanation for the attenuation of the posterior positivity lies in reduced brain responses to repeatedly presented items. This neural “repetition suppression” is well investigated in fMRI studies for recognition of faces, words or objects (e.g., Horner & Henson, 2012; Summerfield et al., 2008) and has also been observed in the EEG (Gruber & Müller, 2005). Contrary to the positivity, the later negativity increased with repetitions, lasted longer and was stronger (larger estimates) in later than in earlier repetitions. Thus, as the offset of the earlier positivity shifted from 400 to 300 ms post picture onset with repetition, the onset of the later negativity shifted from 450 to 400. Independent of the underlying function of this component, one feasible explanation for this pattern is that the posterior negativity was influenced by the preceding positivity in the same location. A strong, early positivity might attenuate the subsequent negativity, as the two are of opposite direction. Similarly, an early offset of the positivity may allow an earlier onset of the subsequent negativity. While future research is necessary to replicate this electrophysiological result pattern and confirm our hypothesis, our overall results clearly indicate that cumulative interference decreases when repeatedly naming the same items. This raises the question about the underlying mechanism responsible for this interaction and whether current models of cumulative interference can explain the strong effect of repetition on the CSI effect observed here. As mentioned earlier, long-lasting repetition priming is well known and behaviourally evidenced as a decrease of overall naming latencies when repeatedly naming the same objects (e.g., Mitchell & Brown, 1988; Wheeldon & Monsell, 1992; Wiggs et al., 2006). It is said to be the result of long-lasting changes to the production system after word production, which make the articulated word more readily available for future production. While some CSI models assume that long-lasting repetition priming and cumulative interference are related (Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010), others argue that they are two distinct effects that do not have the same underlying mechanism (Roelofs, 2018; for empirical evidence, see Hughes & Schnur, 2017). The fact that we found this strong interaction between repetition and cumulative interference could suggest the same underlying mechanism. However, we leave it to the authors of the above -mentioned models to take the present results into consideration, and it remains to be seen which model(s) can accommodate the influence of repetition on cumulative interference.

Cumulative facilitation: We observed cumulative facilitation in the semantic classification task, reflected by a decrease in response times within semantic categories. We assume that the behavioural effect reflects priming of shared semantic features within semantic categories, which increases with each classified category member, making it increasingly easy to perform the classification task (Belke, 2013). Our findings replicate those of previous studies (Belke, 2013; Döring et al., 2022a; Riley et al., 2015) and thus show once more that cumulative context effects can also occur in tasks that do not (necessarily) involve lexical representations. This is expected by models assuming a purely conceptual origin of cumulative interference (Belke, 2013; Roelofs, 2018) but is not as easily explained by those that locate its origin at the interface of the conceptual and lexical level (Howard et al., 2006; Oppenheim et al., 2010). We will come back to this point below.

In line with results from our previous study (Döring et al., 2022a), cumulative facilitation was influenced by repetition. We observed strong facilitation in the first presentation, no linear effect in the first repetition (only a quadratic effect) and a weaker linear effect in the second repetition. Thus, behavioural cumulative facilitation seems to be even more vulnerable to repetition than cumulative interference, which, despite a decrease, was present in all three repetitions (see Döring et al., 2022b for converging results). One explanation for this stronger influence of repetition on cumulative facilitation is that the task involves a binary decision and does not necessitate deep semantic processing. The missing or weak facilitation in Repetition 1 and 2 might be the result of a ceiling effect in the activation of the category-related nodes, induced by the continuous activation of task-relevant natural and man-made features. According to Belke (Belke, 2013), the connections between pictures and their corresponding natural or man-made features should have been strengthened after Repetition 0. Thus, all items would receive some activation when an item of the same classification type (natural or man-made) is being classified, independent of its semantic category. This permanent activation might exceed any additional activation the item receives from category members, resulting in overall shorter reaction times but weak within-category facilitation with repetition. This is what we observed (for a more detailed explanation, see Döring et al., 2022b).

On an electrophysiological level, cumulative facilitation was indexed by an early (100 - 250 ms) component, probably reflecting object processing of task-relevant features. The next component was an increased positivity within the N400 window in the first classification instance (Repetition 0). As mentioned in the discussion of Experiment 2, we interpret this effect as a reduction of the N400, as its time course , spacial distribution and polarity are comparable to other semantic priming studies discussing the N400 (semantic classification/judgement tasks: Geukes et al., 2013, McPherson & Holcomb, 1999; picture-naming: Blackford et al., 2012; Lorenz et al., 2021). In the context of the current study, we assume that the reduction of the negativity with each classified category member reflects the increasing ease with which semantic information is accessed due to priming by the semantically related category members (Belke, 2013). This ERP modulation was heavily influenced by repetition, as we found no such effect in the repetitions (Repetition 1 and 2). Thus, the strong decrease of the behavioural facilitation effect after the first classification instance (decreasing from 88ms to about 16ms from Repetition 0 to 2) seems to be directly mirrored by the (disappearing) posterior positivity in the N400 time window. The symmetry of the behavioural and electrophysiological results with regards to repetition clearly suggest that the increased positivity/reduced negativity reflects cumulative facilitation in the semantic classification task. In the course of the experiment, task-relevant features shared with many items (belonging to either the man-made or natural category) may become more relevant than specific semantic features within categories. This might also explain why we did not observe a significant correlation between the positivity in the N400 window and reaction time.

The third ERP component in the classification task was a posterior negativity between 450 and 600ms after picture onset, where amplitudes decreased with each classified category member. This component was not influenced by repetition but was strongly correlated with reaction times. This suggest that this component is part of the neurocognitive signature of cumulative facilitation. As we observed a similar component in Experiment 1, we will discuss its function below when comparing the two context effects.

Comparing both context effects: When comparing the two experiments, the symmetry of the behavioural as well as the electrophysiological results is striking. Behaviourally, the same items induced cumulative context effects of opposite directions in the two different tasks, and both context effects decreased with repetitions. Furthermore, the combined analysis of the behavioural data showed that cumulative interference can be used as a predictor for cumulative facilitation, replicating results from our previous study (Döring et al., 2022a). Together, these results provide corroborating evidence for a functional link between the two context effects (Belke, 2013). Our findings are predicted by models that assume a purely conceptual origin of cumulative context effects (Belke, 2013; Roelofs, 2018). However, they are not as easily explained by those that argue for an origin at the interface of the conceptual and lexical level (Howard et al., 2006; Oppenheim et al., 2010), as their proposed mechanisms responsible for cumulative effects obligatorily involve the activation of lexical information, which is not necessary in the classification task. There is, of course, the possibility that the lexical level is automatically activated during the classification task due to automatic spreading activation from the conceptual to the lexical level. Under this assumption, a learning mechanism located between the conceptual and lexical level might also explain cumulative facilitation, provided that lexical activation and not lexical selection suffices for the learning mechanism to kick in, as it is unlikely that lexical selection occurs in tasks that do not require overt speech production (for a more detailed discussion, see Belke, 2013; Döring et al., 2022a; for empirical evidence along those lines, see Navarrete et al., 2021). This, however, remains speculation until computational implementations show that these models can account for the present data.

One observation that seems to contradict the interpretation that cumulative interference and cumulative facilitation have a common origin is the fact that we found semantic similarity to influence the former but not the latter (see also Döring et al., 2022a). After all, if the two share the same underlying mechanism, one would expect semantic similarity to affect both context effects in a similar manner. As already discussed in Döring et al. (2022a), it is likely that there was too little variation in the semantic similarity variable to significantly modulate the facilitation effect. After all, all category members were chosen to be closely related, as we did not plan to systematically investigate the influence of this variable on cumulative facilitation. As the facilitation effect is much smaller than the interference effect (smaller estimates, see also Döring et al., 2022b), any contribution of semantic similarity on the facilitation effect might have been more difficult to detect (see also Lorenz et al., 2021). To systematically test the influence of semantic similarity on cumulative facilitation, one would have to include a greater variability of this variable to the material, as has been done in picture naming studies (e.g., Rose & Abdel Rahman, 2017; Rose et al., 2019). However, there is another explanation for the lack of an influence of semantic similarity in classification: Facilitation within semantic categories (or within response categories) might be solely driven by those shared features that identify the items as man-made/natural entities (e.g., category mammals: animal = natural). The semantic similarity variable we used in the analysis, however, was based on participants' ratings on all features the category members shared (e.g., mammals: 4 legs, fur, animal, breathing, etc). Thus, our semantic similarity variable might simply not reflect the features responsible for the facilitation effect and thus not be a good predictor for it. Future research is necessary to verify these hypotheses.

The electrophysiological data provide additional evidence that both context effects are closely related. Both context effects seem to be indexed by a positive ERP component at posterior sites followed by a negative ERP component in the same location. The positive modulation observed in picture naming started earlier than the one observed in the classification task (naming: 250ms post picture onset; classification: 350ms). Above, we interpreted the component in the picture naming task as an indicator for lexical retrieval, and the effect in the classification task as a reduced N400, reflecting semantic priming, which seem to suggest two entirely different ERPs components. Alternatively, these ERP effects, with their similar signatures, might partly reflect the same underlying processes, involving conceptual-semantic processing. After all, lexical interference has a conceptual-semantic origin (Abdel Rahman & Melinger, 2011, 2019; Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010 and many others). In picture-word interference, a modulation of the N400 was interpreted as conceptual-semantic priming - leading to enhanced lexical competition (Blackford et al., 2012). Moreover, most models of speech production assume bidirectional links between the conceptual and lexical level, allowing for parallel processing. This has recently been shown in an empirical study (Lin et al., 2022). Interestingly, another recent study found that a posterior positivity in picture naming reflected both a facilitatory effect of high semantic richness and an inhibitory effect of high feature density (Rabovsky et al., 2021), showing that the same electrophysiological component can be related to opposite behavioural effects. Thus, cumulative (lexical-semantic) interference and cumulative (semantic) facilitation seem to be reflected by a similar ERP component, because of the strong overlap in time and (brain) space. Now, one might wonder why lexical-semantic processing in picture naming has an earlier temporal onset than semantic processing in picture classification. Here, empirical evidence suggests that lexical-semantic processing is accelerated by the top-down intention to speak in tasks that require overt naming, compared to tasks where no overt naming is necessary (Strijkers et al., 2012).

The second ERP component we observed in both experiments was a posterior negativity starting around 450ms post picture onset. The time course, topography, and polarity suggest that it is the same component in both experiments, namely the posterior negativity that has been reported by some previous continuous naming studies (Kuhlen & Abdel Rahman, 2021; Rose & Abdel Rahman, 2017). As mentioned earlier, it has been suggested that this effect reflects the learning mechanism responsible for cumulative interference after the successful selection of a target (Rose & Abdel Rahman, 2017), by strengthening the connections between concepts and their semantic features (Belke, 2013) or between concepts and lexical representations (Howard et al., 2006; Oppenheim et al., 2010). In the current study, we hypothesized that we would find a similar late negativity in the classification task, if this component indeed reflected the learning mechanism behind cumulative context effects. And we did. Our results might thus be taken as evidence in favour of this interpretation, which would provide corroborating evidence in favour of a common conceptual origin of both context effects.

There are two things to consider, though. First, our additional analysis showed that the late negativity observed in Experiment 1 cannot be used as a predictor for the late negativity in Experiment 2, which could suggest that they do not reflect the same component. This, however, could also simply be due to the influence of repetition on the component in Experiment 1 (see above). Second, if the component indeed reflected the learning mechanism, namely long-lasting changes to the production system (strengthening of links between representations, e.g., Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010), one might have expected a positive instead of a negative modulation. This is because studies investigating long- or short-lag priming, with a presumably similar underlying mechanism, have predominantly found that repetition priming is indexed by positive modulations (e.g., Guillaume et al., 2009; Henson et al., 2004; Kiefer, 2005). Thus, it is obvious that still more research is necessary to fully understand this late negative component, and which processes it reflects in cumulative context effects.

5. Conclusion

The aim of the current study was to investigate cumulative interference found in picture naming and cumulative facilitation found in semantic classification tasks by looking at their electrophysiological signatures. From two experiments, we report three key findings: 1. Both cumulative context effects are reflected by a posterior positivity followed by a negativity in the same location. 2. Cumulative interference and cumulative facilitation are affected by repetition, both in the behavioural and the electrophysiological data. 3. The behavioural cumulative interference effect can be used to predict the cumulative facilitation effect. All these commonalties indicate a functional link between the two effects, which suggests that cumulative semantic interference and cumulative facilitation share a common origin at the conceptual origin.

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Appendix A: Stimuli

Category	**Item No**				
	1	**2**	**3**	**4**	**5**
Accessoires (accessories)	Tuch (kerchief)	Hut (hat)	Mütze (cap)	Brille (glasses)	Schal (scarf)
Bürobedarf (stationary)	Klammer ((paper)clip)	Zettel (notepad)	Stift (pen)	Lineal (ruler)	Schere (scissors)
Gebäude (buildings)	Laube (pergola)	Hütte (hut)	Mühle (mill)	Burg (castle)	Villa (villa)

Gemüse (vegetables)	Salat (lettuce)	Sellerie (celery)	Tomate (tomato)	Kohl (cabbage)	Zwiebel (onion)
Geschirr (crockery)	Teller (plate)	Tasse (cup)	Glas (glass)	Becher (mug)	Schüssel (bowl)
Getränke (drinks)	Saft (juice)	Bier (beer)	Schorle (spritzer)	Wasser (water)	Wein (wine)
Insekten (insects)	Assel (pill bug)	Käfer (bug)	Biene (bee)	Laus (louse)	Spinne (spider)
Kleidung (apparel)	Hose (trousers)	Mantel (coat)	Bluse (blouse)	Hemd (shirt)	Rock (skirt)
Körperteile (body parts)	Zahn (tooth)	Nase (nose)	Finger (finger)	Mund (mouth)	Bauch (belly)
Lebensmittel (food)	Käse (cheese)	Quark (quark)	Wurst (sausage)	Schinken (ham)	Salami (salami)
Meerestiere (marine animals)	Krabbe (crab)	Fisch (fish)	Hai (shark)	Wal (whale)	Qualle (jellyfish)
Möbel (furniture)	Tisch (table)	Regal (shelf)	Schrank (wardrobe)	Sessel (arm chair)	Bett (bed)
Pflanzen (plants, incl. mushrooms)	Baum (tree)	Pilz *mushroom*	Blume (flower)	Palme (palm tree)	Busch (shrub)
Säugetiere (mammals)	Maus (mouse)	Katze (cat)	Hund (dog)	Hase (hare)	Hamster (hamster)
Süßspeisen (confectionary)	Kuchen (cake)	Torte (gateau)	Pudding (set custard)	Keks (biscuit)	Eis (icecream)
Trage- behälter (bags)	Tasche (purse/bag)	Ranzen (school bag)	Beutel (pouch/bag)	Koffer (suitcase)	Tüte (plastic bag)
Transport-mittel (transportation)	Boot (boat)	Schiff (ship)	Kutsche (carriage)	Wagen (car/truck)	Jet (jet plane)
Werkzeuge (tools)	Säge (saw)	Hammer (hammer)	Nagel (nail)	Zange (pliers)	Dübel (dowel/plug)
Filler	Flöte (flute), Schloss (lock), Bon (receipt), Drucker (printer), Schlüssel (key), Tonne (bin), Karton (cardboard box), Karte (map), Gitarre (guitar), Münze (coin), Tafel (slate), Kissen (pillow), Bürste (hairbrush), Schein (note), Wecker (alarm clock), Schnee (snow), Küste (shore), Stein (stone), Sturm (tornado), Wüste (desert), Nest (bird's nest), Nebel (mist), Mond (moon),Blitz (lightning), Ballen (bale of hay), Wiese (meadow), Erde (soil), Pfütze (rpuddle), See (lake), Insel (island)				

Appendix B: Figures and Tables

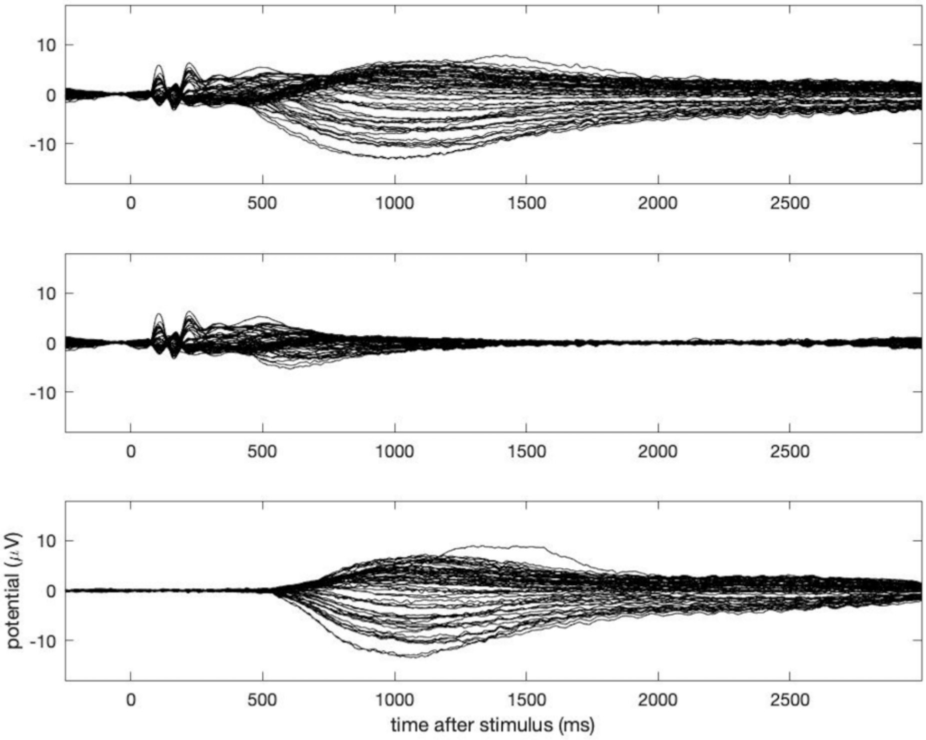


Figure 1: Separation of compounds for artifact corrections with RIDE. Top: Original ERPs prior to speech artifacts correction. Bottom: R- component, containing response-related artefacts which were removed from original ERP to create S-component. Middle: S- component free of articulation- related noise, which was used for the data analysis.

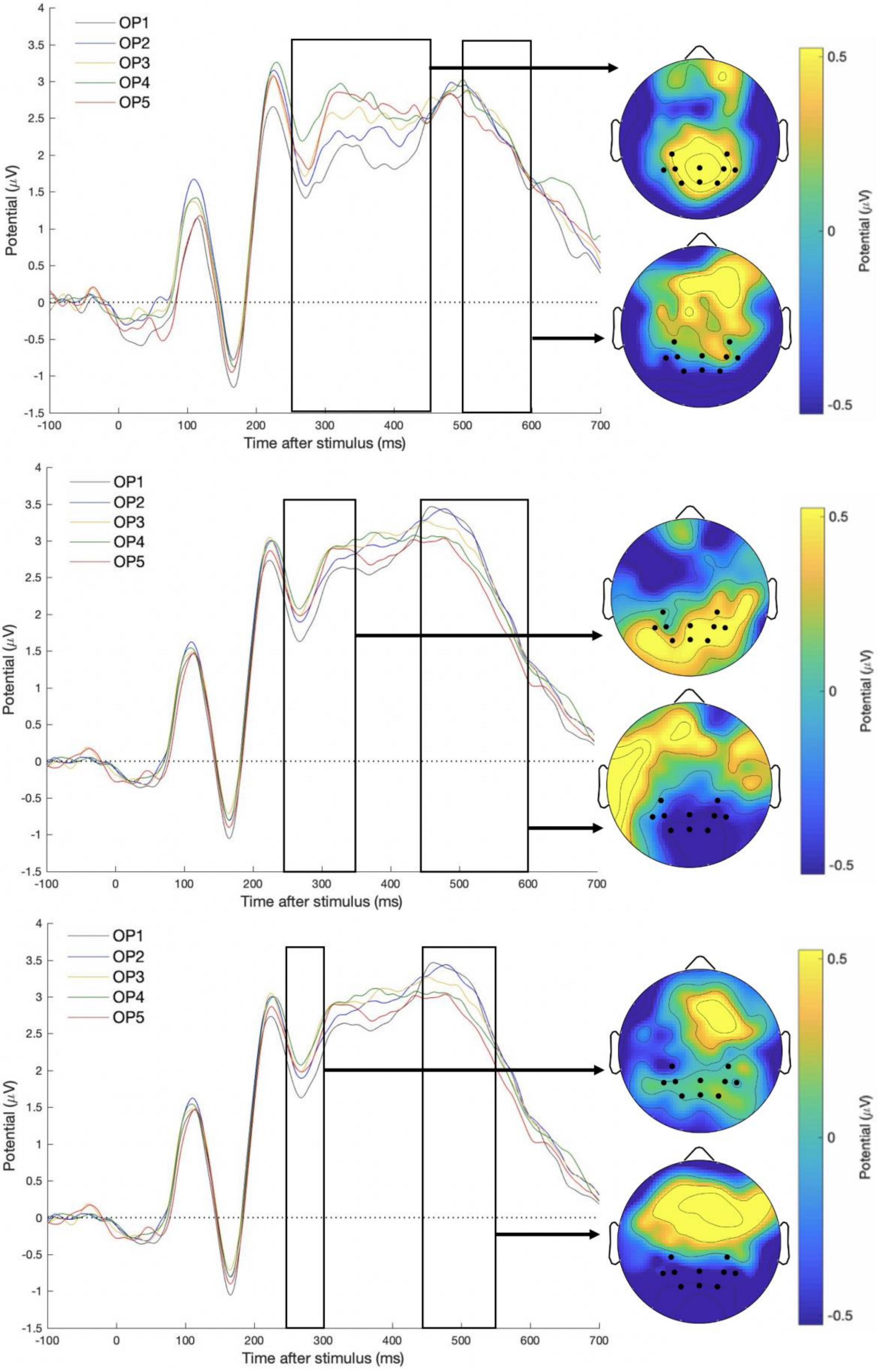
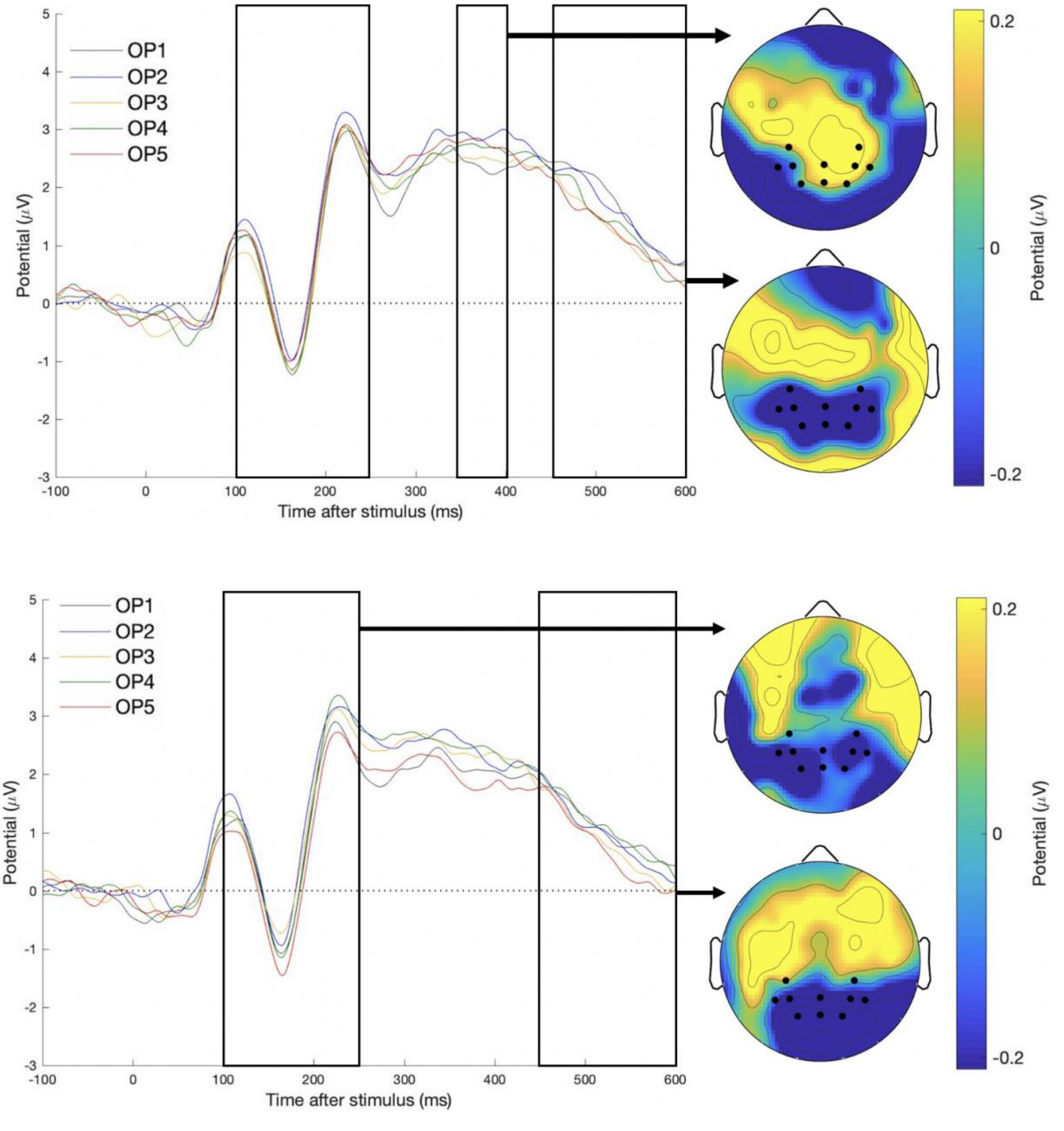

OP1
OP2
OP3
OP4
OP5
Potential (μV)
Time after stimulus (ms)
-100
0
100
200
300
400
500
600
700
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
0.5
0
-0.5

Figure 2. ERPs and Topographies for each of the three naming cycles observed in Experiment 1 (Repetition 0 (top), Repetition 1 (middle), Repetition 2 (bottom). For the ERPs, the electrodes of interest at posterior sites were pooled. The black boxes indicate significant linear modulations observed in the main analysis or the nested models. The topographies depict time windows of significant effects. They show the difference between Ordinal position 5 and 1 (i.e., the last minus the first category members).



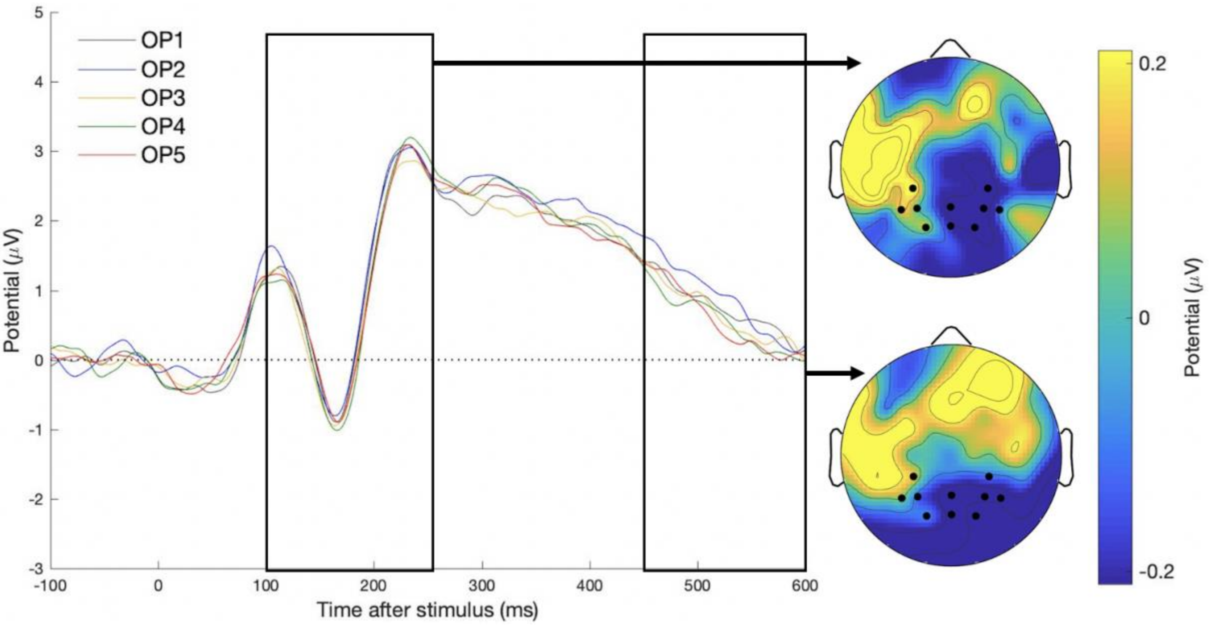


Figure 3. ERPs and Topographies for each of the three classification cycles observed in Experiment 2 (Repetition 0 (top), Repetition 1 (middle), Repetition 2 (bottom)). For the ERPs, the electrodes of interest at posterior sites were pooled. The black boxes indicate significant linear modulations observed in the main analysis or the nested models. The topographies depict time windows of significant effects. They show the difference between Ordinal position 5 and 1 (i.e., the last minus the first category members).

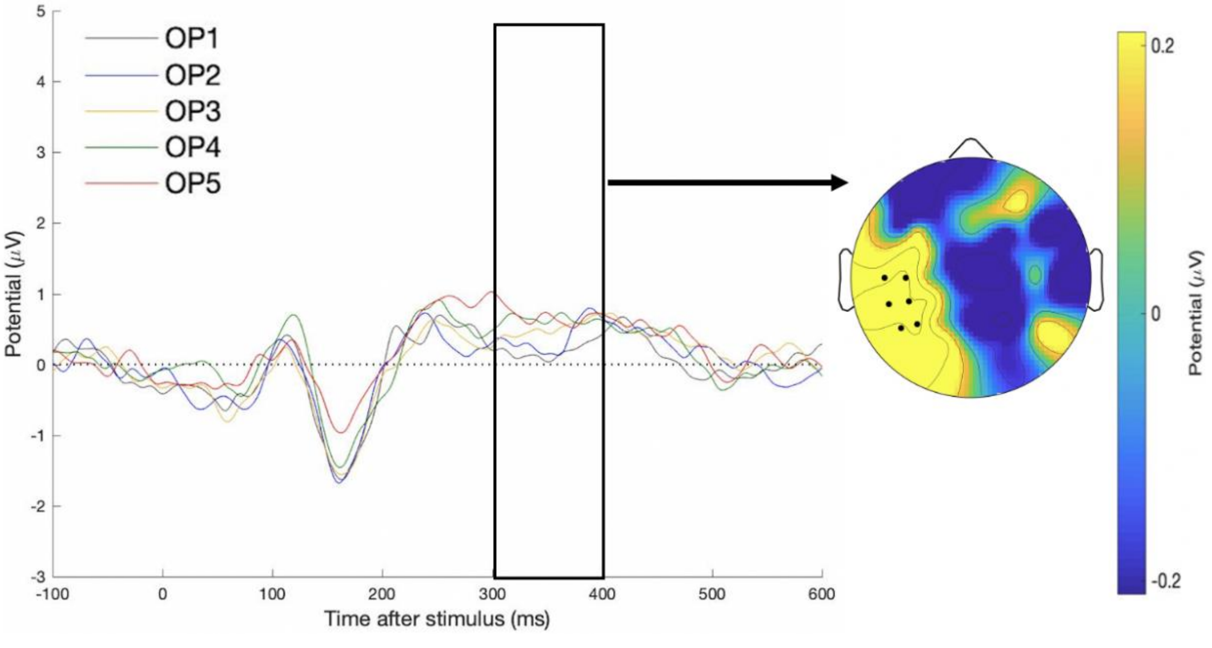


Figure 4: Topography of increasing positivity in the N400 window (300-400ms) at left temporal sites in Repetition 2 (post-hoc analysis). For the ERP, the electrodes of interest at left temporal sites were pooled. The black box indicates the time window pf the significant linear modulation depicted in the topography. The topography shows the difference between Ordinal position 5 and 1 (i.e., the last minus the first category members).

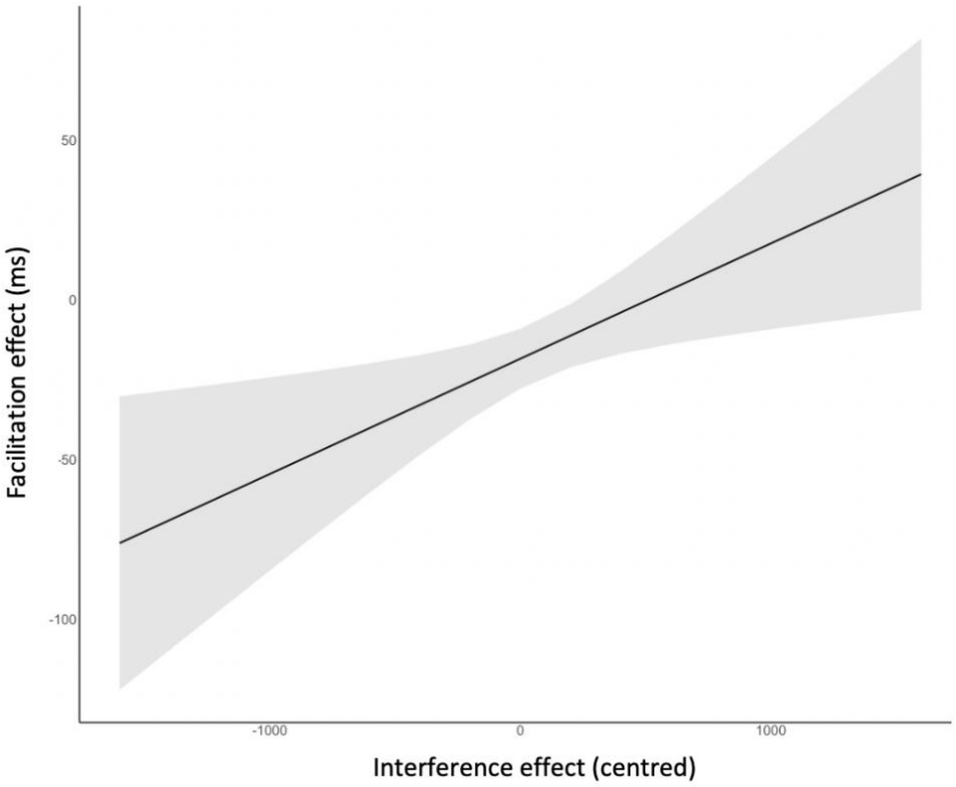


Figure 5. Visualisation of the results from the additional analysis: main effect of the interference effect (centred) on the facilitation effect. A large interference effect (i.e., high positive numbers = strong interference) predicts a small facilitation effect (high negative numbers = strong facilitation).

Table 1: Results of the additional LMM-analysis reported in Experiment 2.
log(facilitation effect) ~ Interference effect*Repetition+ Interference effect *Semantic similarity + Interference effect:sem_simic:repc +(0+repc||subject)

	log(ec)			
Predictors	*Estimates*	*std. Error*	*t-value*	*p*
(Intercept)	7.59	0.00	3220.03	**<0.001**
Interference effect	0.00	0.00	2.68	**0.007**
Repetition	0.01	0.00	4.36	**<0.001**
Semantic similarity	0.01	0.01	1.42	0.156
Interference effect* Repetition	**0.00**	**0.00**	**0.62**	**0.532**
Interference effect* Semantic similarity	-0.00	0.00	-0.45	0.654
Interference effect*Repetition*Semantic similarity	-0.00	0.00	-0.26	0.793
Random Effects				
σ^2	0.01			

$\tau_{00\ \text{subject}}$	0.00
ICC $_{\text{subject}}$	0.01
Observations	1524
Marginal R^2 / Conditional R^2	0.021 / 0.029

Table 2: Results of LMMs at left temporal ROI (all presentation cycles) in Experiment 2.

	Repetition 1			**Repetition 2**		
Time window (ms)	***t***	***p***	***rho***	***t***	***p***	***rho***
300-350	1.84	0.07	n.s.	3.12	<0.01	n.s.
350-400				1.93	0.05	n.s.
400-450						
450-500				1.77	0.08	n.s.

Table 3. Reanalysis of the behavioural data reported in Rose & Abdel Rahman (2017):
-1000/RT ~ Semantic distance*Ordinal position*Repetition+ Trial +(Semantic distance+Semantic distance:Ordinal position+Repetition||Subject)+ (1| Item)

	-1000/RT			
Predictors	*Estimates*	*std. Error*	*t-value*	*p*
(Intercept)	-1.127	0.027	-42.308	<0.001
Semantic distance (close vs. distantly related)	0.027	0.009	3.104	0.005
Ordinal position	0.035	0.004	8.450	<0.001
Repetition	-0.101	0.010	-10.656	<0.001
Trial	0.000	0.000	5.373	<0.001
Semantic distance * Ordinal position	0.068	0.011	6.458	<0.001
Semantic distance* Repetition	-0.002	0.004	-0.488	0.626
Ordinal position * Repetition	-0.010	0.005	-1.990	0.047
Semantic distance* Ordinal position * Repetition	-0.001	0.010	-0.142	0.887
Random Effects				
σ^2				0.04
$\tau_{00\ \text{item\_id}}$				0.02

$\tau_{00\ \text{subject}}$	0.00
$\tau_{00\ \text{subject.1}}$	0.00
$\tau_{00\ \text{subject.2}}$	0.00
$\tau_{00\ \text{subject.3}}$	0.01
$\text{ICC}_{\text{item\_id}}$	0.31
$\text{ICC}_{\text{subject}}$	0.01
$\text{ICC}_{\text{subject.1}}$	0.02
$\text{ICC}_{\text{subject.2}}$	0.02
$\text{ICC}_{\text{subject.3}}$	0.18
Observations	13508
Marginal R^2 / Conditional R^2	0.059 / 0.433

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On the lexical representation(s) of compounds: A continuous picture naming study

Anna-Lisa Döring[1], Rasha Abdel Rahman[1], Pienie Zwitserlood[2] & Antje Lorenz[1]

[1]Department of Psychology, Neurocognitive Psychology, Humboldt-Universität zu Berlin

[2]Department of Psychology and Otto Creutzfeldt Center for Cognitive and Behavioral Neuroscience, Westfälische Wilhelms-Universität Münster

Corresponding author:

Anna-Lisa Döring, Humboldt-Universität zu Berlin, Department of Psychology,

Rudower Chaussee 18, 12489 Berlin, Germany.

Phone: +49 – 30 – 2093-4904

Email: anna-lisa.doering@hu-berlin.de

Abstract

The lexical representation of compound words in speech production is still under debate. While most studies with healthy adult speakers suggest that a single lemma representation is active during compound production, data from neuropsychological studies point towards multiple representations, with activation of the compound's constituent lemmas in addition to the compound's lemma.

This study exploits the cumulative semantic interference effect to investigate the lexical representation of compounds in speech production. In a continuous picture naming experiment, category membership was established through the compounds` first constituents (category animals: *zebra crossing, pony tail, cat litter ...*), while the compounds themselves were not semantically related. Moreover, pictures depicting the compounds' first constituents (*zebra, pony, cat ...*) were presented as a control condition. As expected, naming latencies within categories increased linearly with each additionally named category member when producing monomorphemic words, which is interpreted as increasing interference during lexical selection. Importantly, this cumulative semantic interference effect was also observed for compounds. This indicates that the lemmas of the compounds' first constituents were activated during compound production, causing interference due to their semantic relationship and thereby hampering the production of the whole compound. The results are thus in line with the multiple-lemma representation account (Marelli et al., 2012). We argue that the apparent contradiction between results of previous studies with healthy adult speakers and our current study can be explained by the different experimental paradigms used.

Keywords: noun-noun compounds, lexical representation, speech production, cumulative semantic interference, semantic transparency

1. Introduction

Retrieving words from lexical memory is at the heart of effective speech production, and many studies have investigated how words are processed during speaking and how they are represented in memory. A prominent model of speech production assumes two levels of lexical representation, an abstract lexical level, the so-called lemma level, containing the word's syntactic properties, and a (morpho-phonological) word-form or lexeme level (e.g., Levelt et al., 1999; for a contrasting account, see Caramazza, 1997). While morphologically simple words (e.g., *fish*) are assumed to have one lemma and one word-form entry, it is still under debate how morphologically complex words, in particular compounds (e.g., *goldfish*), are represented at these levels. Are they stored holistically (*goldfish*) like simple nouns or are the morphological constituents represented separately (*gold* and *fish*) and then assembled on-line?

Many studies on compound production point towards morpheme-sized representations at the word-form level instead of compound-sized word forms (e.g., Bien et al., 2005; Lorenz & Zwitserlood, 2016; Lorenz et al., 2018b; Lüttmann et al., 2011; Roelofs, 1996; but see Janssen et al., 2008; Janssen et al., 2014). Research on the lemma representation of compounds, however, is sparse and results are partially inconsistent (e.g., Lorenz & Zwitserlood, 2016; Lorenz, Mädebach, & Jescheniak, 2018; Lorenz et al., 2021; Marelli et al., 2012; Mondini et al., 2004; Semenza et al., 1997). The current study provides new experimental data from speech production on the lexical representation of compounds at the lemma level and aims to shed light on the thus far inconsistent results on the topic.

1.1 The representation and production of compounds

A central aspect of successful word production concerns lexical-semantic encoding, namely the "translation" of a preverbal, conceptual message into words. While there are different psycholinguistic models describing this process, they all share at least the following two assumptions: 1. lexical-semantic encoding includes at least two levels, a conceptual and a lexical level, and 2. conceptually related lexical entries are initially co-activated before the target entry is selected from among the activated items (e.g., Caramazza, 1997; Dell et al., 1997; Levelt et al., 1999; Mahon et al., 2007; Roelofs, 2018; Schade, 1999).

The two-stage model by Levelt and colleagues (1999) assumes two lexical levels, a lemma and a word-form level. At the lemma level, the syntactic properties of a word, including gender and number, are specified, whereas information about its (phonological) word form is stored at the lexeme or word-form level (Levelt et al., 1999). When producing a noun while naming a picture (e.g., the German word *Fisch*$_{\text{masc/sing}}$, fish), speech production is assumed to proceed as follows: The picture (fish) first activates the object's preverbal conceptual information and the corresponding lexical concept, before activation spreads to its lemma representation, which includes grammatical information about the word, such as grammatical gender (masculine) and number (singular). Simultaneously, due to spreading activation at the conceptual level (Collins & Loftus, 1975), semantically related concepts are co-activated (e.g., other members of the category "marine animal" such as *whale, dolphin*, and associates such as *fin, ocean*), which in turn activate their own lemma representations. Due to bidirectional spread of activation, all activated lemmas further activate their respective concepts, resulting in reciprocal activation of related concepts and their lemmas. From this cohort of co-activated items, the target lemma has to be selected before the corresponding phonological word form (/fɪʃ/)is retrieved (Levelt et al., 1999, see also Abdel Rahman & Melinger, 2009, 2019; Damian & Bowers, 2003; Mahon et al., 2007; Roelofs, 1992, 2018, but see Caramazza, 1997; Dell et al., 1997; Schade, 1999).

For compounds, Levelt and colleagues (1999) claim that lexicalised compounds (such as "goldfish") have a single, "holistic" lemma (*goldfish*) but morpheme-sized (decomposed) word form representations (/gəʊld/ and /fɪʃ/; for an opposing view, see Janssen et al., 2008). More recently, neuropsychological studies on participants with aphasia suggest that compounds may have more than one lemma representation, namely constituent-based lemmas in addition to holistic compound lemmas. In this view, the holistic lemma (*goldfish*) as well as the constituent lemmas (*gold* and *fish*) are selected, before activation spreads to the corresponding (morpheme-sized) word-form representations (e.g., Marelli et al., 2012).

The single-lemma account (e.g., Levelt et al., 1999) has received support from studies with healthy adult speakers. Lüttmann et al. (2011), for example, investigated compound production in a picture-word interference (PWI) task. In this task, a picture is named while a simultaneously presented (written) distractor word is to be ignored, and previous studies have shown that naming latencies are longer when distractor and target are categorically related than when unrelated (e.g., Damian & Bowers, 2003; Glaser & Düngelhoff, 1984; Glaser & Glaser, 1989; Schriefers et al., 1990). This interference effect is taken to reflect competition at the lemma level, which, due to spreading activation at the conceptual level, would be greater for semantically related than unrelated items (Levelt et al., 1999; Roelofs, 1992, 2018; for a different explanation, see e.g., Mahon et al., 2007). In the PWI-study by Lüttmann and colleagues (2011), the categorically related distractor words were either related to the whole compound (e.g., *suitcase* → *HANDBAG*), or to one of its constituents (e.g., *cake* → *<u>BREAD</u>KNIFE; saucer* → *EARCUP*). Semantic interference was obtained for distractors related to the compound, not for distractors merely related to one of its constituents. If, during compound production, the compounds' constituent lemmas were indeed activated in addition to the compound lemma, the categorical relationship of the distractor and the compound's first constituent should cause (at least some) interference (see also Lorenz, Regel, et al., 2018; Lorenz et al., 2021). Further evidence comes from grammatical gender effects in compound production. In a determiner-priming study, Lorenz, Mädebach, & Jescheniak (2018) observed that compound naming was facilitated when participants were presented head-congruent determiners, while no such priming effect could be observed for modifier-congruent determiners. This suggests that the gender information of the modifiers was not activated during compound production, in line with a single-lemma representation of compounds (for contrasting data from aphasia, see Lorenz et al., submitted).

Empirical evidence supporting the multiple-lemma account mainly comes from neuropsychological studies that tested participants with aphasia suffering from syntactic word-category deficits (e.g., Marelli et al., 2012). These individuals have difficulties processing a certain syntactic word-category, such as verbs or nouns, a deficit that is taken to reflect a functional impairment at the lemma level (e.g., Bastiaanse & Van Zonneveld, 2004; Crepaldi et al., 2006; Berndt et al., 1997) where the syntactic information of words is assumed to be represented (e.g., Levelt, 1989; Levelt et al., 1999). Interestingly, this impairment also persists when naming compounds containing the particular syntactic category, such as verb-noun compounds. Studies showed that verb-impaired aphasic speakers have more difficulties producing verb-noun compounds (such as *blowfish*) than noun-noun compounds (e.g., Lorenz et al., 2014; Mondini et al., 2004; Semenza et al., 1997; see also Marelli et al, 2012 for evidence from reading aloud). As verb-noun compounds are nouns and should thus not pose a problem for these speakers, they seem to have accessed the syntactic information (i.e., lemmas) of both constituents, which points towards a decomposed lemma representation. In addition to the evidence from neuropsychological studies, there are some indications from studies with healthy adult speakers in favour of multiple lemmas. First, Lorenz et al. (2018) reported significantly more picture-naming errors in a PWI study when the distractor word was semantically related to the compound's modifier (e.g., *moon* → *SUNflower*) compared to unrelated distractors. Although this effect was small and not mirrored by the naming latencies, it seems to point to the existence of multiple lemma representations. Further evidence comes from a PWI study on semantically transparent and opaque compounds (Lorenz & Zwitserlood, 2016). Here, semantic transparency refers to the meaning relation between the compound as a whole and its constituents. The meaning of a transparent compound (e.g., *Zahnbürste* (toothbrush)) is closely related to the meaning of both its constituents (*Zahn* (tooth) and *Bürste* (brush)), as they share many semantic features. The meaning of opaque compounds (e.g., *Löwenzahn* (lit. lion tooth - dandelion) cannot (easily) be derived from the meaning of its constituents, as the compound refers to a concept (e.g., a flower) that shares no or very few semantic features with its constituents (Libben et al., 2003)[1]. In a PWI-task with noun-noun compound targets, participants produced determiner-compound phrases, while ignoring semantically unrelated distractor words that were either gender-congruent with the compound target (and thus with its head), with the compound's modifier, or with both compound constituents. In this task, naming is faster when the otherwise unrelated distractor is gender-congruent with the picture name, an effect attributed to gender priming (e.g., La Heij et al., 1998; Schiller & Caramazza, 2003; Schriefers, 1993; Schriefers & Teruel, 2000). A gender-congruency effect was only observed for semantically transparent compounds, when both constituents were gender-congruent with the distractor. For semantically opaque compounds and targets with constituents of different gender, no congruency effects were observed (Lorenz & Zwitserlood, 2016). It thus seems that the modifier's gender receives some activation during compound production, which again would support a multiple-lemma representation (Marelli et al., 2012). Furthermore, this study indicates that semantic transparency might modulate the representation of compounds at the lemma level, such that separate representations of the constituents might only play a role for semantically transparent compounds, but not for opaque ones (Lorenz & Zwitserlood, 2016).

One possible reason for these contrasting results might be that modifier-related effects of compound targets are likely to be rather weak and thus not easily detectable. This is because the multiple-lemma account assumes a hybrid representational format of compounds, with constituent-specific lemmas only in addition to a holistic compound lemma (Marelli et al., 2012). This implies that - during NN-compound production - activation will spread to the holistic lemma entry of the compound as well as to the two constituent lemma entries. Thus, a modifier lemma as part of the complex compound representation is likely to receive less

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[1] Please note that the relatedness-definition of semantic transparency is one possible way to define/describe the transparency of compounds. More recently, the notion of semantic compositionality has been discussed in literature on compound processing (e.g., Günther & Marelli, 2018; Libben et al., 2003; Marelli & Luzzatti, 2012)). Here, transparency is defined in terms of predictability, meaning that a compound is assumed to be transparent when its meaning is easily predictable from the meaning of its constituents.

activation than the lemma of a simple noun, resulting in weaker interference for modifier-related distractors in compound naming (*moon* → *sunglasses*) than for semantically related distractors in simple noun naming (*moon* →*sun*). Furthermore, the modifier likely also receives less activation than the compound's head at the lemma level because the head carries the syntactic properties and, for compounds with a transparent head, also the core meaning of the compound, whereas the modifier constituent usually adds to this meaning (cf. Gagné et al., 2020). This complex lemma construct is assumed to be hierarchical, meaning that the lexical concept first activates the holistic lemma representation of the compound, which in turn activates the connected constituents' lemmas[2], similar to the super-lemma model proposed for idiomatic phrases (e.g., *kick the bucket*) by Sprenger and colleagues (2006).

The aim of the present study was thus to investigate the lemma representation of compounds by means of a paradigm that allows for stronger effects of modifiers in compound naming than PWI: the continuous picture naming paradigm (Brown, 1981; Howard et al., 2006). Investigating different aspects of word production, studies using this paradigm have reported strong and robust effects (e.g., Belke & Stielow, 2013; Costa et al., 2009; Hoedemaker et al., 2017; Howard et al., 2006; Kuhlen & Abdel Rahman, 2017; Navarrete et al., 2010; Oppenheim, 2018; Oppenheim et al., 2010; Rose & Abdel Rahman, 2016, 2017; Runnqvist et al., 2012). Thus, if modifier-related effects are indeed small and thus not easily detectable, the continuous picture naming paradigm may provide a valuable tool to tackle this problem.

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[2] Note that Marelli et al. (2012) assume that this hierarchical, complex lemma structure can be bypassed under particular conditions, for example when the compound is embedded in a sentence. Here, the lemma representation can, in some cases, directly activate the corresponding constituents at the lexeme level due to syntactic information provided by the preceding sentence context. In their Experiment 2, Marelli and colleagues (2012) presented VN-compounds embedded in sentences, where all compounds were preceded by a determiner. Their aphasic subject, who in bare compound reading had trouble reading the verb-constituents of the compounds, was suddenly able to read the whole compounds without difficulties. The authors interpret this as evidence that the constituent verb lemmas were inhibited as the reader would expect to find a noun after a determiner. This way, according to their explanation, activation could spread directly from the holistic compound lemma to the constituents' word forms, resulting in improved reading performance.

1.2 Cumulative semantic interference in the continuous picture naming paradigm

In the continuous picture naming paradigm, several members of different semantic categories (e.g., *fish, whale, shark, dolphin, octopus* for the category *marine animals*) are presented for naming in a seemingly random order, separated by 2 to 8 unrelated objects (these are either members of other categories or filler items; e.g., Howard et al., 2006). Naming latencies within each category increase in a linear fashion with each ordinal position, that is, as a function of previously named pictures of the same category. This cumulative semantic interference effect is independent of the number of intervening unrelated items, but studies have shown that it is modulated by the semantic similarity of the category members, with stronger interference effects for semantically close than for less close items (e.g., Rose & Abdel Rahman, 2017). The effect is interpreted in terms of increasing competition on the lexical level, strengthened by each member of the same category (Belke, 2013; Howard et al., 2006; Roelofs, 2018; Rose & Abdel Rahman, 2016, 2017; for alternative interpretations, see Mahon et al., 2007; Navarrete et al., 2010; Oppenheim, 2018; Oppenheim et al., 2010).

However, activation and decay within the lexical system are short-lived and thus not suitable to explain the cumulation and longevity of the interference effect. Therefore, additional learning mechanisms have been proposed to account for these effects (Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010). In the tradition of competitive lexical selection, Howard and colleagues (2006) argue that producing a word strengthens the connection between its concept and lexical entry, thus priming its future activation. This is known as repetition priming (Mitchell & Brown, 1988). A subsequently presented object from the same category activates semantically related concepts, including the previously named one. Due to the now strengthened connection between the concept and its lexical representation, its lemma is more strongly activated than previously unnamed related objects, making it a strong competitor in the lexical selection process of the target. As each additional category member adds to the cohort of competing lexical items, the number of strong competitors systematically increases, resulting in cumulative semantic interference (Howard et al., 2006). Oppenheim et al. (2010), on the other hand, explain cumulative interference effects without competitive lexical selection. Here, repetition priming is implemented in terms of error-driven learning, where not only the connection between concept and lexical entry of the target is reinforced, but the connections between concepts and lexical entries of co-activated non-target items are weakened as well. By means of simulations of their computational model, Oppenheim and colleagues demonstrate that including error-driven learning suffices to explain cumulative semantic interference without assuming a competitive selection process. Alternatively, Belke (2013) argues that the learning mechanism is in fact located at the conceptual level, where the links between the target's lexical concept and its semantic features are strengthened after naming. She demonstrates that cumulative facilitation in a semantic classification task and cumulative interference in a naming task interact, suggesting a common conceptual origin of these effects.

While these approaches differ with respect to the origin of the cumulative interference effect and whether or not lexical selection is a competitive process, they all agree that the locus of the interference is at the lexical level, reflecting delayed lexical selection at the lemma level (see Belke, 2013, for a detailed discussion).

1.3 The current study

The current study exploits the cumulative semantic interference effect to investigate the representation and processing of compounds during speech production. In particular, we test whether compounds have a single, holistic lemma or a multiple-lemma representation. In our study, the category membership of the items is established through the compounds` modifiers, while the compounds themselves are not semantically related (e.g., category animals: *Eselsohr* [lit. donkey ear; dog ear (in a book)], *Zebrastreifen* [zebra crossing], *Pferdeschwanz* [lit. horse tail; pony tail], *Mausefalle* [mouse trap], *Katzenstreu* [cat litter]). Additionally, pictures depicting the compounds' modifiers (*Esel* [donkey], *Zebra* [zebra], *Pferd* [pony], *Maus* [mouse], *Katze* [cat]) are presented to be named with simple nouns as a control condition for effects of these constituents.

Due to the specific mechanism of learning-induced effects, the continuous picture naming paradigm is particularly well suited to investigate even subtle semantic interference effects. We assume that semantic context stimuli, such as distractors in the PWI paradigm, typically induce two opposing effects at different levels of processing: priming at the conceptual level and interference at the lexical level (cf. Abdel Rahman & Melinger, 2009; 2019). These two overlapping effects together determine the duration of lexical selection and thus overall naming times. If conceptual priming outweighs lexical interference, the overall outcome will be facilitation, whereas strong lexical activation that outweighs concomitant conceptual priming would result in overall interference. Thus, the polarity and the magnitude of the resulting effect (facilitation, interference or no effect) in a PWI study reflects the net outcome of the trade-off between conceptual priming and lexical interference (cf. Abdel Rahman & Melinger, 2009; 2019). In contrast, in the continuous naming paradigm interference can be captured in the absence of concomitant facilitatory effects. The cumulative increase in naming times for concepts from the same semantic category captures increasing lexical interference without influences of simultaneous conceptual priming. This is because only the interference increases over time due to the learning mechanism that comes into effect once a lemma has been selected for further processing. Conceptual activation and priming, however, decay quickly across intervening trials. In short, while the conceptual facilitation is short-lived and of similar magnitude on each trial, the interference is long-lived and increases with each newly named category member. As a result, cumulative interference is not obliterated by concomitant conceptual facilitation. Thus, the robust cumulative semantic interference can be observed even for semantic associates, for which, in the PWI, lexical interference is not strong enough to outweigh strong simultaneous conceptual priming (e.g., Rose & Abdel Rahman, 2016).

We therefore assume that subtle interference effects for modifiers of compound targets that have thus far only been observed in PWI error data and in neuropsychological studies would be detected in the continuous naming paradigm – if a multiple-lemma representation is activated during compound production. For the compound condition in our experiment, the multiple-lemma account predicts that the categorical relationship between the compounds' modifiers results in cumulative semantic interference: Figure 1 illustrates the hypothesised activation pattern with multiple-lemma representations, when producing the compound *Katzenstreu* (*cat litter*) after previously having produced the modifier-related compound *Mausefalle* (*mouse trap*). The compound's lexical concept first activates its multiple-lemma construct. Current accounts assume that the activation flow between lexical concepts and their lemmas is bidirectional (e.g., Dell & O'Seaghdha, 1992; Levelt et al., 1999). Thus, in case of a multiple-lemma representation, the activated constituent lemmas (*cat* and *litter*) will automatically activate their representations on the conceptual level (in addition to conceptual activation due to the semantic relatedness between the concepts cat, litter and cat litter). In our study, it is the activation of the modifier concept (e.g., *cat* in *cat litter*) that will cause interference. Due to spreading activation at the conceptual level, the concept *cat* will co-activate semantically related concepts, including the concept *mouse*, which was previously activated during the production of *mouse trap*. The corresponding lemma *mouse* will now become a particularly strongly activated competitor in the lexical selection process of the lemma *cat,* delaying its selection and thus delaying the production of the whole compound *cat litter*. The subsequent naming of other compounds with semantically related modifiers would result in an accumulation of interference, manifesting in a linear increase in naming latencies.

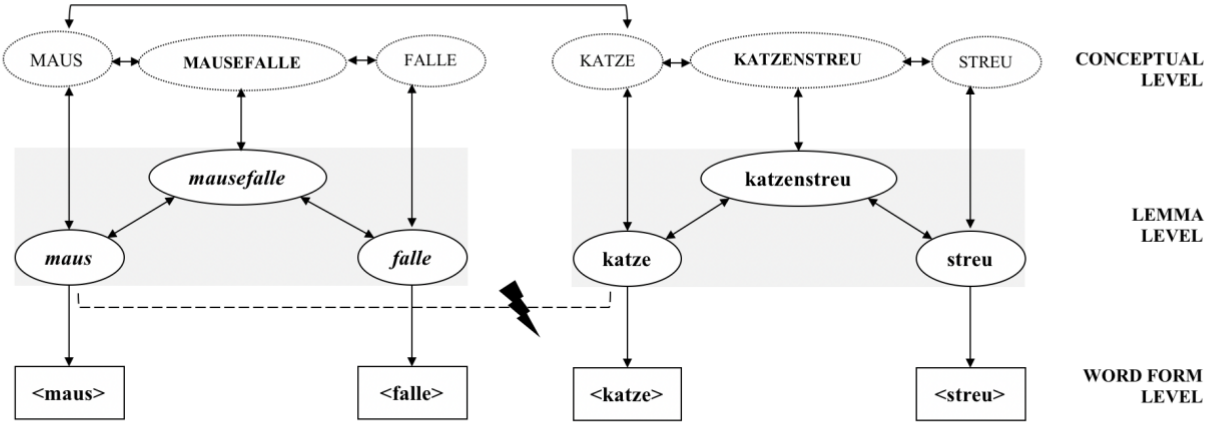

Figure 1: Hypothesised activation pattern with multiple-lemma representations, when naming *Katzenstreu* (*cat litter*) after previously having produced *Mausefalle* (*mousetrap*).

However, if we observe cumulative semantic interference in the modifier-related compound condition, we would expect the interference to be weaker than for simple nouns. This is because the multiple-lemma account assumes a hybrid structure, in which the compound and the head lemma are activated and selected in addition to the modifier lemma. Thus, the activation level of the modifier lemma is likely to be weaker than in the simple-noun control condition, where only one lemma needs to be selected. In contrast, the single-lemma account would predict no cumulative semantic interference for modifier-related compounds, as these are not semantically related overall and thus should not interfere with one another during lexical selection.

Furthermore, cumulative semantic interference might be modulated by semantic transparency of the compound targets. If semantically transparent and opaque compounds differ in terms of lexical representation and processing, as suggested earlier (i.e., multiple lemma representations for transparent compounds and a single lemma for opaque ones; e.g., Lorenz & Zwitserlood, 2016), semantically transparent or semi-transparent compounds may show stronger semantic interference than opaque compounds. Thus, we will include measures of semantic transparency into the analysis of our data to control for this possibility. However, transparency is not an experimental factor in the design of our study.

Due to the categorical relationship of the items, we expect to find robust cumulative interference in the simple noun control condition, reflected by a linear increase of naming latencies with each ordinal position, as a function of previously named pictures of the same category. Based on previous studies (e.g., Rose & Abdel Rahman, 2016), we assume the magnitude of the interference effect in both word-type conditions to be modulated by the semantic similarity of items, that is, stronger interference for more closely related items within categories. Finally, we expect faster reaction times for simple nouns than for compounds, as they are more frequent and shorter in length.

2. Material and methods

2.1 Participants

Thirty-six German native speakers (24 female, 12 male) between the age of 18 and 35 (mean 26.3 years) took part in the experiment. The sample size was chosen following a power analysis (simr package, Green & Macleod, 2016). Based on a previous experiment using linear mixed-effects models to analyse data from a continuous picture naming study with simple-noun targets (log-transformed data), we predicted an effect size (*b)* of about 0.02 for the interference effect in the simple noun (control) condition (i.e., ordinal position effect for simple nouns in the nested model; here, the *b*-value of 0.02 corresponds to an average increase in naming latencies of about 19 ms from one category member to the next (cf. Kuhlen & Abdel Rahman, 2017)). As we expected the interference effect in the compound condition to be smaller, we used a *b* of 0.01 when simulating the outcome of the anticipated model with 1000 iterations for the compound condition. With 36 participants we reached a power estimate of 80% (95% confidence interval: 66.28, 89.97) for detecting the hypothesized cumulative semantic interference in the compound condition. All participants had normal or corrected-to-normal vision and received monetary compensation or course credit for their participation. The study received ethical approval from the ethics committee of Humboldt-Universität zu Berlin.

2.2 Materials

The stimulus set consisted of 260 items, including 180 targets (90 noun-noun compounds and their 90 modifiers as simple nouns), 60 filler items (30 compounds, 30 simple nouns) and 20 practice items (10 compounds, 10 simple nouns). The targets belonged to 18 different semantic categories (e.g., *body parts, animals*), with five members each. Category membership applied to the compounds' modifiers (*Fußball* (football), *Handschuh* (lit. hand shoe - glove), *Kopfsalat* (lit. head salad - lettuce), *Halskrause* (lit. neck ruff – neck brace), *Armbrust* (lit. arm chest - crossbow), while care was taken that the heads, and thus the compounds themselves, were not semantically related. All filler and practice items were semantically unrelated to the targets, and we ensured that there was no morphological overlap, that is, no constituent appeared more than once in the stimulus set.

To establish a measure for semantic similarity, an online survey preceded the main experiment. Eighty native speakers of German (mean age: 37.5 years; range: 18-76) took part in the survey (20 participants per item pair). The participants were presented with two members of a category at a time and were asked to use a six-point Likert scale (6 = very closely related; 1 = not at all related) to indicate the semantic similarity of the two items. Semantically similar items were defined as sharing many semantic features (e.g., *apricot* and *plum*: both are fruits, can be eaten, grown on trees, have a stone, are round …), while items with few or no shared features were defined as semantically distant (e.g., *apricot* and *telephone*). For each material set, participants either rated the two compounds (e.g., *zebra crossing* and *cat litter*), or their modifiers as simple nouns (e.g., *zebra* and *cat*)[3]. The results showed that the compounds of one "category" were perceived as not related (mean rating overall: 1.9, *SD* = 1.2, range 1.2-3.3), while the modifier nouns were judged as related (mean: 4.5, *SD* = 1.3, range 2.9-5.3, $t = 78.46$, $p < 0.0001$). To control for the possibility that semantic transparency modulates a potential

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[3] We included filler items to ensure that participants also had to rate closely related compound pairs and distantly related simple nouns.

interference effect in the compound condition, a second rating assessed the transparency of the compounds. A different group of German native speakers (N = 20, mean age: 29.5 years, range 18-40) evaluated the semantic relation between each of the two constituents of the compound and the compound itself (N = 90), providing two measures per compound (see Libben et al., 2003; Lorenz & Zwitserlood, 2014). For the item *football*, for example, participants evaluated two separate statements, namely *The meaning of ball is included in the meaning of football* and *The meaning of foot is included in the meaning of football*. They used a 6-point Likert scale (6 = The statement is completely true; 1 = The statement is not true at all). Although the lists included semantically fully transparent, semi-transparent and fully opaque compound targets, the majority of the items was transparent. The mean transparency of modifier constituents was 4.5 (*SD* = 1.42; range 1.65-5.8) and 4.9 for head constituents (*SD* = 1.35, range 1.9-5.9).

Afterwards, 260 coloured photographs depicting all target, filler, and practice items were chosen. For the compound targets, we carefully selected pictures that did not depict the compounds' modifiers (i.e., the picture for the compound target *belt buckle* did not depict the belt, but only the buckle itself). This way, any modifier-related effects could not be attributed to simple activation of the modifier concept by the visual stimulus. However, in 9% of the compound pictures (8 pictures), the modifier concept had to be present on the picture in some way to ensure that participants would be able to identify the pictures as the intended compound concept (e.g., *ginger tea*). All photographs were scaled to 3.5cm x 3.5cm and had a homogenous light grey background. Appendix A lists all materials used.

2.3 Apparatus

Participants were seated in a noise-cancelling booth, approx. 80 cm from the screen and approx. 30 cm from the microphone. The pictures were presented on a 19" inch screen (1280x1024), using version 17.0 01.14.14 of the software Presentation® (Neurobehavioural

Systems, Inc, www.neurobs.com). Response times were registered by a voice-key (manufactured in house) and a Sennheiser MKH 416 P48 microphone.

2.4 Experimental design

Eighteen different lists were created on the basis of a master list that contained 90 slots for the target words and 30 slots for the filler items (for comparable procedure, see Belke, 2013). The five slots for the five members of a category were separated by lags of 2, 4, 6 or 8 intervening items (e.g., Howard et al., 2006). Eighteen of 24 possible lag orderings were selected. Care was taken that each lag value (i.e., 2, 4, 6, and 8) was about equally represented at each ordinal position (i.e., each lag value was presented a total of 3 to 4 times at each of the ordinal positions, from 2 to 5). For each list, the semantic categories were allocated to the relevant category slots in such a way that each category appeared at a different category location designated in the master list, thus ensuring a unique order in which categories appeared within each list. Furthermore, the order of presentation of the five items of each category differed in each list. Care was taken to keep semantically related categories (e.g., mammals and insects) and semantically related items from different categories (e.g., *Nasenbär* (lit. nose bear (coati) - category: face parts) and *Beutelratte* (lit. bag rat (opossum - category: (carrying) containers) apart.

The word types (compounds, simple nouns) were presented block-wise, thus every list was split into two blocks, each containing 45 critical and 15 filler items in the compound or simple noun condition. To directly compare the processing of compounds and simple nouns, two versions of each of the 18 lists were created and presented to different participants. In version one, participants were shown the photographs of simple nouns (e.g., *Zebra* (zebra)) in block one and photographs of compounds in block two (e.g., *Zahnbürste* (tooth brush)). In version two, participants were shown the corresponding compounds in the first block (e.g., *Zebrastreifen* (zebra crossing)) and simple nouns in the second (e.g., *Zahn* (tooth)). This counterbalanced order ensured that each participant named both compounds and simple nouns, with only one item from a compound-simple noun pair per participant. Every participant completed five differently randomised versions of their list, to enhance statistical power and to further investigate the effect of repetition on the cumulative semantic interference effect. To ensure that participants did not have to switch between the two word-type conditions, we used a blocked design.

2.5 Procedure

Prior to each word-type condition (compounds, simple nouns), there was a familiarisation phase. Participants were presented with the 70 pictures and corresponding labels of the items of the upcoming word type condition (45 targets, 15 filler items, 10 practice items) in a random order on the screen (one picture at a time) and were asked to remember the correct label. They moved on to the next picture by themselves and thus had as much time as needed during the familiarisation phase. In the main experimental session, a fixation cross was shown for 500 ms at the start of each trial, followed by the picture. The picture was presented until a response was initiated or for a maximum of 2500 ms, which was also the time-out measure for responses. After an inter-trial interval of 2 seconds, the next trial started. Participants were instructed to name the pictures as fast and as accurately as possible, using the label they had seen during the familiarisation phase. Naming latencies (reaction times) were recorded with the help of a voice-key, which marked the time that elapsed between the onset of the picture and the onset of the naming response, and the experimenter coded any voice-key or naming errors (incorrect responses, stuttering etc.).

2.6 Analysis

The data analysis was done with R (R Development Core Team, 2017). Naming latencies were analysed for test trials only. Trials in which pictures were named incorrectly or dysfluently (3.09%) or in which the voice-key triggered too late (RT > 2500ms; 0.01%) were excluded from the analysis. For outlier identification, we combined light a-priori screening for artefactual responses (RT < 300 ms) with a removal of outliers outside the normal distribution of the final model's residuals (for more details on the procedure, see Baayen & Milin, 2010). The a-priori screening resulted in an exclusion of 0.79% of the data, while a further 2.55% were excluded after model fitting (standardised residuals > than 2.5). The inversely transformed reaction times[4] were fitted with a series of linear mixed effect models (LMM; Baayen et al., 2008) using the function lmer of the R package lme4 (Bates et al., 2015) and *p*-values were computed with the lmerTest package (Kuznetsova et al., 2017).

For the main analysis, model comparisons were performed to identify the best fitting model, starting with the maximal model, including a maximal random effects structure (cf. Barr et al., 2014) and a four-way interaction of word type (compound vs. simple noun), ordinal position (five ordinal positions of members within one category), repetition (repetitions 1-5) and semantic similarity (mean values from semantic similarity rating), a two-way interaction of word type and lemma frequency[5] as well as trial number and word length as covariates. The model was first simplified by successively removing those random effects that explained zero variance according to singular value decomposition (e.g., Bates et al., 2015) until the maximal informative model was identified. The fixed effects structure was then reduced by successively excluding interaction terms and/or covariates, and then compared until the simpler model explained the data significantly worse than the more complex one (significant $\chi 2$ test in the anova function). The final model used for the main analysis included main fixed effects and three-way interactions of word type, ordinal position, and repetition, and of word type, ordinal position, and semantic similarity. Lemma frequency and trial number were included as

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[4] We used the boxcox function to identify the best transformation for our data (-1000/RT). However, untransformed RTs yielded similar results.

[5] The normalised lemma frequency was extracted from the dlex database (Heister et al., 2011).

covariates. The random structure included random intercepts for subjects, items, and semantic category and random slopes for word type for each participant, item, and category (omitting correlations to facilitate convergence). The predictor word type was contrast-coded using effect-coding, while the predictor ordinal position was contrast-coded using polynomial contrasts. Polynomial contrasts test for a linear trend in the data (among others), that is, is the increase in response times from ordinal position 1 to 5 linear or not. The cubic and quadratic trends were excluded from the analysis as they did not improve the model fit (for more details on contrast-coding, see Schad et al., 2020). The three predictors repetition, semantic similarity, and lemma frequency were centred and entered as continuous variables. The predictor semantic similarity included the results of the semantic similarity rating for the modifiers, that is, the same value for each item in the compound and the simple noun condition.

To investigate if any potential increase in reaction time was due to general slowing rather than our semantic context manipulation, we conducted a second analysis in which we subdivided all lists into subcycles of five consecutive items. If general slowing was responsible for the increase in naming latencies, then pictures named later in a subcycle should be named more slowly than those named earlier. We used the same model as in the main analysis but substituted the predictor ordinal position for the predictor position within subcycle (five consecutive trials, i.e., position 1-5). This predictor was, like ordinal position, contrast-coded using polynomial contrast.

As we had specific hypotheses about how semantic transparency might influence the interference effect of compound targets, we conducted a third analysis that only included targets in the compound condition. Here, the constituent-related transparency of the modifier and the head were included as continuous covariates (centred). As in the main analysis, we started with a maximal model, reducing it until the best fitting model was identified. The final model’s fixed effects structure included main fixed effects of ordinal position, modifier transparency, head transparency, repetition, semantic similarity, trial number and lemma frequency. In addition, two-way interactions were included for ordinal position and modifier transparency, ordinal position and head transparency, ordinal position and repetition as well as ordinal position and semantic similarity. The random structure included random intercepts for subjects, items, and categories.

3. Results

Main analysis: Table 1 contains all results of the LMM analysis. As expected, simple nouns were named faster on average than compounds (792 ms and 885 ms, respectively). While this difference was not significant (main effect: word type) [6], lemma frequency significantly influenced naming latencies (main effect lemma frequency). Furthermore, there was a significant main effect for ordinal position, reflecting an overall linear increase of reaction times from one ordinal position to the next within categories. Importantly, this cumulative semantic interference differed for simple nouns and compounds (interaction: word type x ordinal position). While naming latencies for simple nouns increased by 59 ms from ordinal position 1 to 5, the increase for compounds was only 36 ms, as illustrated in Figure 2. A post-hoc analysis using a nested version of the same model confirmed cumulative semantic interference in both word type conditions, but showed that the magnitude of the effect was indeed larger for simple nouns (b: 0.04, $SE = 0.004$, $t = 12.05$, $p < 0.001$) than compounds (b: 0.02, $SE = 0.004$, $t = 5.10$, $p < 0.001$)[7]. Interestingly, this difference was modulated by semantic similarity (interaction: word type x ordinal position x semantic similarity) but not by repetition (interaction: word type x ordinal position x repetition). Here, the nested model showed that the interference effect

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[6] Please note: When not including the predictor lemma frequency into the model, there is a significant main effect for word type ($t = 3.95$, $p < 0.001$), reflecting the descriptive results, namely that compounds were named slower than simple nouns. This suggests that this word type difference was greatly driven by the lemma frequency of the items.

[7] When including all polynomial trends into the analysis of the nested model, we also found a quadratic trend in the data. This, however, was true for compounds (b= -0.020, SE= 0.006, $t = -3.373$, $p = 0.001$) and simple nouns ($b = -0.026$, $SE = 0.006$, $t = -4.456$, $p < 0.001$). Thus, the word type conditions do not seem to differ in any other respect than the magnitude of the linear increase.

observed in the simple noun condition was modulated by semantic similarity, that is, cumulative interference was stronger with higher semantic similarity (simple nouns: ordinal position x semantic similarity: $b = 0.03$, $SE = 0.008$, $t = 3.24$, $p = 0.001$). In contrast, this could not be observed in the compound condition (compounds: ordinal position x semantic similarity: $b = -0.01$, $SE = 0.008$, $t = -1.53$, $p = 0.13$). Overall, there was a main effect of trial and a main effect of repetition, showing that, as expected, participants became faster with each repetition cycle. While the main analysis indicated that the overall interference effect was affected by repetition (interaction: ordinal position x repetition), post-hoc analyses for each repetition cycle confirmed that the interference effect was present in each of the five repetitions, but varied in magnitude (Rep1: $b = 0.04$, $SE = 0.006$, $t = 6.33$, $p < 0.001$, Rep2: $b = 0.04$, $SE = 0.006$, $t = 7.60$, $p < 0.001$, Rep3: $b = 0.03$, $SE = 0.006$, $t = 5.63$, $p < 0.001$, Rep4: $b = 0.03$, $SE = 0.006$, $t = 5.86$, $p < 0.001$, Rep5: $b = 0.02$, $SE = 0.006$, $t = 3.16$, $p = 0.002$; see Figure 1 in Appendix B for visual illustration).

Analysis of naming latencies within subcycles: The results of the subcycle analysis revealed a nonsignificant decrease within subcycles (main effect Position in subcycle: $t = -0.385$, $p = 0.71$), an effect that was not influenced by word type (Position in subcycle x word type: $t = -1.113$, $p = 0.27$) or repetition (Position x Repetition: $t = -1.385$, $p = 0.17$), nor by the interaction of the two (Position x Word type x Repetition: $t = -0.62$, $p = 0.54$; see Figure 3 for visual illustration and Table 1 in Appendix B for the full model output), indicating that participants' naming latencies did not increase throughout the experiment as a result of general slowing.

Analysis of compound targets: Table 2 contains the LMM output of the analysis of compound targets only. Overall, the results mirror those of the main analysis, namely significant main effects for ordinal position, repetition, trial, and lemma frequency, as well as no main effect for semantic similarity of modifier constituents within compounds and no interaction of semantic similarity and ordinal position (see Table 2). Transparency also did not affect overall naming latencies (no main effects for Transparency modifier or Transparency head). However, there was a significant interaction of ordinal position and head transparency, suggesting that greater head transparency resulted in a stronger interference effect. Modifier transparency, on the other hand, did not significantly influence the magnitude of the observed effect (interaction: Ordinal position x Transparency modifier).

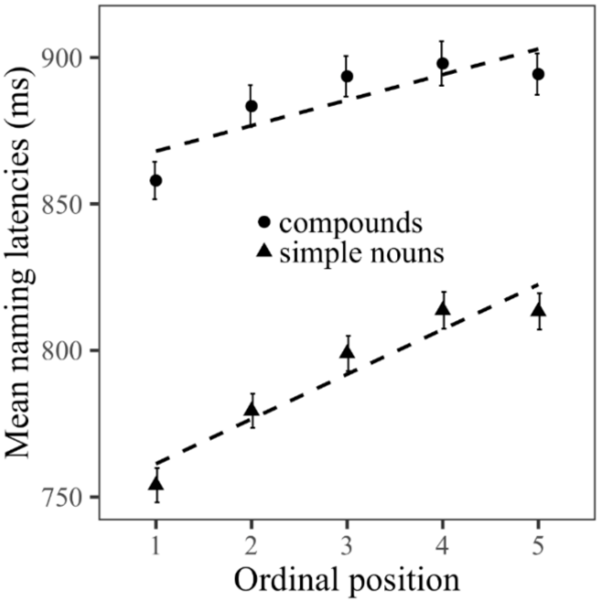
Note that our pretest on semantic similarity showed that the compounds themselves were not semantically related (see Section 2.2.). Following this, their semantic relationship should not have been responsible for the observed interference effect in the compound condition. Nevertheless, we wanted to exclude this option and conducted an additional post-hoc analysis for the compound targets, including the semantic similarity ratings of the compounds. The semantic similarity values were entered as a centred covariate into the model (for model information and the full model output, see Appendix B, Table 2). The results confirmed that the semantic similarity of the compound targets did not significantly influence the interference effect in the compound condition (Ordinal position x Semantic similarity compounds: $t = -0.085$, $p = 0.932$).

Table 1
Main analysis: Fixed-effect estimates, standard errors, t- values and p-values; estimates of the variance and standard deviations of the random effects.
Model: -1000/RT ~ Word type * Ordinal position * Repetition + Word type * Ordinal position * Semantic similarity + Lemma frequency + Trial + (Word type || subject) + (Word type || Category) + (Word type || Item)

	-1000/RT			
Predictors	*Estimates*	*std. Error*	*t-value*	*p*
(Intercept)	-1.284	0.032	-40.648	**<0.001**
Word type	0.022	0.041	0.540	0.591
Ordinal position	0.032	0.003	11.974	**<0.001**
Repetition	-0.055	0.003	-18.346	**<0.001**
Semantic similarity	0.036	0.026	1.376	0.173
Trial	< 0.001	< 0.001	5.427	**<0.001**
Lemma frequency	-0.069	0.015	-4.721	**<0.001**

Word type x Ordinal position	-0.025	0.005	-4.900	**<0.001**
Word type x Repetition	-0.016	0.003	-5.950	**<0.001**
Ordinal position x Repetition	-0.005	0.002	-2.941	**0.003**
Word type x Semantic similarity	-0.088	0.046	-1.927	0.058
Ordinal position x Semantic similarity	0.007	0.006	1.189	0.234
Word type x Ordinal position x Repetition	0.006	0.004	1.705	0.088
Word type x Ordinal position x Semantic similarity	-0.037	0.011	-3.361	**0.001**

Random effects	**Variance**	**Sd**
Subject (Intercept)	0.023	0.15
Subjects (Word type)	0.007	0.08
Category (Intercept)	0.005	0.07
Category (Word type)	0.011	0.11
Item (Intercept)	0.006	0.08
Item (Word type)	0.020	0.14
Residuals	0.051	0.23



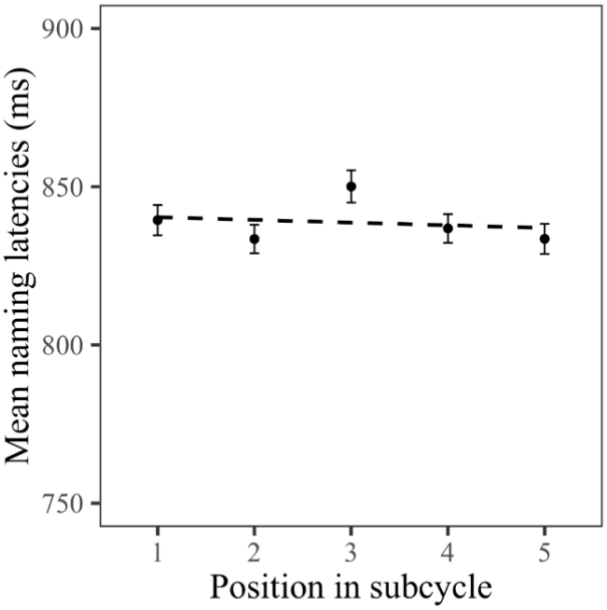


Figure 2 (left). Mean naming latency and standard error (in milliseconds) for each ordinal position, collapsed across repetitions and broken down by word type. The line represents the slope of the linear trend of the interference effect.

Figure 3 (right). Mean naming latency and standard error (in milliseconds) for five consecutive trial(positions) within subcycles, collapsed across repetitions. The lack of an increase in naming latencies within subcycles illustrates that participants did not generally slow in the course of the experiment.

Table 2
Analysis of compound targets: Fixed-effect estimates, standard errors, t- values and p-values; estimates of the variance and standard deviations of the random effects.
Model: Ordinal position* Transparency modifier + Ordinal position* Transparency head + Ordinal position* Repetition+ Ordinal position* Semantic similarity + Trial + Lemma frequency + (1| Subject) + (1| Category) +(1|Item)

	-1000/RT			
Predictors	*Estimates*	*std. Error*	*t-value*	*p*
(Intercept)	-1.272	0.036	-35.346	<0.001
Ordinal position	0.014	0.004	3.634	<0.001
Transparency modifier	0.013	0.009	1.476	0.143
Transparency head	-0.001	0.012	-0.056	0.955
Repetition	-0.088	0.008	-10.992	<0.001
Semantic similarity	-0.014	0.026	-0.531	0.598
Trial	0.001	<0.001	5.091	<0.001
Lemma frequency	-0.068	0.017	-3.967	<0.001
Ordinal position x Transparency modifier	-0.001	0.003	-0.385	0.701
Ordinal position x Transparency head	0.009	0.004	2.241	0.025
Ordinal position x Repetition	-0.002	0.003	-0.870	0.385
Ordinal position x Semantic similarity	-0.011	0.008	-1.368	0.171

Random effects	**Variance**	**Sd**
Subject (Intercept)	0.03	0.35
Category (Intercept)	0.00	0.01
Item (Intercept)	0.01	0.11
Residuals	0.05	0.05

4. Discussion

The aim of the current study was to investigate the representation and processing of compounds during speech production. More specifically, we wanted to explore whether compounds are stored as holistic entities at the lemma level (single-lemma account; e.g., Levelt et al., 1999) or whether they have multiple lemma representations, that is, constituent-sized lemmas in addition to the holistic compound lemma (multiple-lemma account; e.g., Marelli et al., 2012). To test this, we exploited the cumulative semantic interference effect found in the continuous picture naming paradigm.

We observed the expected linear increase in the simple-noun control condition, with naming latencies increasing by about 15 ms for each additionally named member of a category (e.g., category *body*: Fuß (foot) < Hand (hand) < Kopf (head) …). This cumulative semantic interference is due to the close semantic relationship of the category members, and replicates results of previous continuous picture naming studies (e.g., Belke, 2013; Howard et al., 2006; Oppenheim et al., 2010). Furthermore, the magnitude of the effect was modulated by the semantic similarity between the category members. More closely related items caused greater interference (cf. Rose and Abdel Rahman, 2017). Our main finding, however, is the observed cumulative interference in the compound condition, where compounds were unrelated but their modifiers belonged to the same semantic category (e.g., category *body*: *Fußball* [football], *Handschuh* [lit. hand shoe – glove], *Kopfsalat* [lit. head salad – lettuce, etc). Here, naming latencies increased by about 9 ms from one category member to the next. Additional analyses showed that this interference was not due to semantic relatedness of the compound targets, nor does it reflect general slowing in picture naming (Fig. 3). Thus, the cumulative interference in this condition can only be attributed to the semantic relationship between the compounds' modifiers, suggesting that their lemmas were activated during compound production (cf. Figure 1). Consequently, our data are in line with the predictions made by the multiple-lemma representation account (e.g., Marelli et al., 2012). This is thus the first study to provide evidence from reaction time data that constituent lemmas are activated when healthy adult speakers produce a compound word.

Other studies have reported results that are best explained by the single-lemma account (Levelt et al., 1999; e.g., Lorenz, Mädebach, & Jescheniak, 2018; Lorenz et al., 2021; Lüttmann et al., 2011), or have only found weak evidence for multiple lemmas in their naming error analysis (e.g., Lorenz, Regel, et al., 2018). As discussed above, we believe that the discrepancy in results between those previous studies and the present one is due to the different experimental paradigms used. Specifically, we assume that modifier-related effects are too small to be detected in the PWI task, due to concomitant conceptual facilitation obliterating the interference. In contrast, the continuous naming paradigm we used is more sensitive to detect interference because it reveals learning-induced long-lasting interference in the context of short-lived, non-increasing conceptual priming. Thus, even weak interference, as induced by our semantically-related modifiers, can be captured because it is not cancelled out by concomitant facilitation (e.g., Abdel Rahman & Melinger, 2019). That modifier-related effects are indeed weaker than whole-word related effects is also mirrored by our results. We obtained significantly less cumulative semantic interference in the compound than in the simple-noun condition. This weaker interference could also be the reason why we did not find a modulation of the effect by the semantic similarity of the modifiers in the compound condition, contrary to the simple noun condition. As the estimates of the nested LMM indicate that the effect for the latter is more than double in size, the influence of the predictor semantic similarity might have been easier to detect than in the compound condition.

While the different paradigms are the most likely explanation for the discrepancy in results between our study and previous ones, there are two alternative explanations linked to the design of our study. First, one could argue that our participants were particularly aware of the morphological structure of our items, which might have resulted in a different way of processing the compounds. In our blocked design, participants had to produce only simple nouns in the first and only compounds in the second half of the experiment (or vice versa), whereas participants only produced compound targets in previous PWI studies (e.g., Lorenz et al., 2021). Our participants might therefore have noticed the morphological structure of the compounds, particularly when presented after the simple words, and might have processed their constituents more consciously. Previous research has shown that awareness of the constituents leads to different processing of lexicalised compounds, rendering the constituent representations more salient and thus more highly activated (e.g., Lorenz et al., 2019). To test this idea, we ran an analysis including the order in which participants named the two word-type conditions as factor. The results show that the order did not influence the ordinal position effect in either word-type condition (word type x ordinal position x order: $t = 1.309$, $p = 0.19$), meaning that the interference effect for compounds (and for simple nouns) was the same, whether they were named in the first or the second half of the experiment (for the full model output, see Table 3 in Appendix B). Thus, the interference observed in the compound condition is unlikely due to participants' greater awareness of the morphological structure of the stimuli. A second potential explanation for the presence of modifier effects is that they were induced by those visual stimuli that explicitly depicted the modifier concept (less than 9%). However, a post-hoc re-analysis of the data confirmed that the modifier effect was strongly present when excluding these items from the analysis ($b = 0.021$, $SE = 0.004$, $t = 5.319$, $p < 0.001$, using the same linear-mixed model structure as in the original analysis). Thus, the interference in the compound condition can also not be attributed to the simple activation of the modifier constituents by some of the visual stimuli.

Apart from our main finding, namely that the constituents' lemma representations are activated when producing a compound, the additional analysis of the compound targets showed that the observed interference effect was influenced by the transparency of the compounds' heads. Compounds with more transparent heads showed greater cumulative interference than those with less transparent heads[8]. We did not find a comparable effect for modifier transparency. Before discussing these effects further, we want to point out again that semantic transparency was not a factor manipulated in our design and was thus not balanced across

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[8] This observation was confirmed by a post-hoc analysis. We split the dataset equally into a high- and a low-head transparency set (median split at 5.2 (based on mean transparency rating)). While the interference effect was present in the LMM-analysis of the high-head-transparency dataset (Main effect Ordinal position: $b = 0.022$, $SE = 0.005$, $t = 3.96$, $p < 0.001$), no such effect could be observed for the low-head-transparency items ($b = 0.009$, $SE = 0.005$, $t = 1.596$, $p = 0.111$). The contrast-coding was identical to that in our main analysis. The model structure was as follows: -1000/RT ~ Ordinal position *Repetition + Ordinal position*Semantic similarity+ Trial+Lemma frequency + (1|Subject)+ (1| Category) +(1|Item)

experimental items and categories. As explained in the material section above, on a continuum, the majority of our compound items (about 70%) was judged as being more transparent than opaque (heads as well as modifiers). Thus, there is a likely lack of statistical power, particularly for more opaque constituents. The following interpretations of the transparency effects are thus made with caution and it is necessary to conduct further experiments that are explicitly designed to investigate the lemma representation of different kinds of compounds to corroborate the effects observed here.

A first possible explanation for the influence of head transparency on the interference effect is that the lemma representation of compounds is mainly modulated by the heads' transparency. Compounds with a more transparent head (*Fußball* (*football*); *Kopfsalat* (lit. *head salad - lettuce*) might thus have a complex, multiple-lemma representation, while those with a more opaque head (*Handschuh* (lit. *hand shoe – glove*) might only be represented in a single, holistic lemma. While some studies on compound comprehension (e.g., El-Bialy et al., 2013; Gagné et al., 2020, Isel et al., 2003; Libben et al., 2003; Sandra, 1990; but see Ji et al., 2011; Zwitserlood, 1994; see Schäfer, 2018 for a recent overview) and written compound production (Gagné & Spalding, 2014, 2016) have observed that the transparency of the head seems to play a key role in compound representation and processing, this interpretation raises some non-trivial questions. How could and why should such a complex lemma structure evolve?

In many languages, such as German, compounding is a productive word formation process, allowing for the generation of new, morphologically complex words on the fly (e.g., *Corona-Ampel* [Covid traffic light]). The generation of such words, however, necessarily involves access to constituent representations of the intended compound when it is produced for the first time. A holistic lemma representation might emerge later on. It seems likely that the constituent lemmas are not simply replaced by this holistic representation, but that all representations are more or less activated during production, depending on co-activation of the compound (*football*) and the constituents (*foot* and *ball*) at the conceptual level. The level of co-activation would, of course, be heavily influenced by the semantic transparency of a compound's constituents. For more transparent compounds, the constant co-activation at the conceptual level likely leads to direct links between compound and constituent lemmas. This complex lemma structure likely facilitates compound production compared to a single, holistic lemma, as the additional activation the constituent lemmas receive from their conceptual representations would further activate the holistic compound lemma, and thus speed up compound production (cf. Figure 1). This process would not apply to more opaque compounds (*Eselsohr*, lit. donkey's ear (dog-ear)), due to the missing semantic relation between the compound and its constituents[9]. The complex lemma structure of more transparent compounds would thus result from adaptations within the speech production system to facilitate compound production (along the lines of Libben's "maximization of opportunity" principle (e.g., Libben, 2006)).

This conception, however, has difficulties explaining the lacking impact of modifier transparency on the interference effect, which suggests that all modifiers are involved in compound processing, independent of their transparency. There would be no link between a more opaque modifier lemma (*Kopf* in *Kopfsalat* (lit. head salad) - lettuce) and the holistic compound lemma. Of course, it is possible that more opaque modifiers (and heads, for that matter) are (also) coactivated based on some other information not included in our semantic transparency rating (such as visually/ perceptually grounded effects; e.g., Günther et al., 2020). However, it is likely that the failure to observe an effect of modifier transparency on the interference effect is due to the lack of statistical power, which would be even more apparent when looking at modifier-related than head-related effects. After all, the former are expected to be weaker than the latter, as the head provides the compound's syntactic properties and, in case

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[9] It is assumed that most opaque compounds were initially transparent and that over time, due to language change or other influencing factors, the relationship between the compounds and their constituents might have been lost or became less apparent.

of compounds with transparent heads, also its core meaning, and thus has a special status in compound processing.

As this suggests that the modifier effects were mainly driven by more transparent compounds, one could argue that the observed interference simply reflects competition between the compounds' holistic lemmas and their free-standing constituent lemmas, without the latter being part of the compounds' lemma representation. This view, however, would not explain the accumulation of interference within categories. While the modifier lemma would be highly activated in case of coactivation, it would never actually be selected, as it is not the target. Thus, the modifier would not be subject to learning-induced mechanisms responsible for the longevity of cumulative semantic interference (Belke, 2013, Howard et al., 2006, Oppenheim et al., 2010), meaning interference would not be able to accumulate within categories. This, however, is what we found. It is thus necessary to assume that the activated modifier lemmas are part of the compounds' lemma representations, as they would only then be selected.

A second interpretation of the transparency results could be that all types of compounds are represented in a complex lemma structure, as a result of morphological information being stored at or passed down to the holistic compound lemma (cf. particle verbs (e.g., *to look up*), discussed by Levelt et al., 1999). Our head transparency effect could then be explained by greater lemma activation of the strongly activated transparent head constituent, which would increase the activation of the modifier lemma via the holistic compound lemma.

Finally, we briefly consider whether speech production models other than the ones from which we derived the specific predictions tested in our study are able to explain the present pattern of results. Models allowing for bidirectional activation flow between lemmas and their corresponding word forms (Dell, 1986; Dell & O'Seaghdha, 1992; Dell et al., 1997; see also Strijkers & Costa, 2016) seem to predict other effects than the ones obtained here. Given the evidence that all types of compounds, independent of their transparency status, are decomposed at the word form level (Dohmes et al., 2004; Levelt et al., 1999; Lorenz & Zwitserlood, 2016;

Lorenz, Regel, et al., 2018; Lüttmann et al., 2011; Roelofs, 1996), we would expect the morphemes at the word-form level to activate their lemmas in an interactive activation flow. This bottom-up lemma activation of the constituents should lead to co-activation of the semantically-related modifiers, irrespective of the transparency status of the head, which should result in (at least weak) modifier-related effects for all types of compounds, not only, as in our study, for those with a transparent head. If, however, we exclude the transparency effects from the equation and assume a complex lemma structure for all types of compounds, these models would also be able to explain the observed cumulative semantic interference effects.

5. Conclusion

Our study is the first to use the continuous picture naming paradigm to investigate the representation and processing of noun-noun-compounds in speech production. Contrary to many previous experimental studies, our data reveal activation of the compounds' constituents on the lemma level, which corroborates a multiple-lemma representation of compounds (Marelli et al., 2012) that assumes a lexical structure with lemmas for constituents as well as for the compound. The cumulative semantic interference effect seems to be a more sensitive measure to capture modifier-related effects that are not or only weakly present in the PWI task (e.g., Lorenz, Regel et al., 2018; Lüttmann et al., 2011) or other paradigms (e.g., gender-priming; e.g., Lorenz, Mädebach, & Jescheniak, 2018). While the main focus of our study was not on the influence of transparency on the representation of compounds, our data indicate that a multiple-lemma representation might only apply to compounds with a transparent head, while those with an opaque head are more likely to be holistically represented.

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Appendix A: Materials

Category	Item No.				
	1	2	3	4	5
Mammals	Pferdeschwanz horse tail (ponytail)	Zebrastreifen zebra stripes (zebra crossing)	Eselsohr donkey's ear (dog ear)	Mausefalle (mousetrap)	Katzenstreu (cat litter)
Body	Armbrust arm chest (crossbow)	Handschuh hand shoe (glove)	Halskrause neck ruff (neck brace)	Kopfsalat head salad (lettuce)	Fußball (football)
Face	Augenklappe (eye patch)	Zahnbürste (toothbrush)	Nasenbär nose bear (coati)	Stirnband forehead strap (headband)	Lidschatten lid shadow (eye shadow)
Plants	Baumwolle tree wool (cotton)	Heckenschere hedge scissors (head clippers)	Grashüpfer (grasshopper)	Blumenvase flower vase (vase)	Strauchtomate bush tomato (vine tomato)
Bag types	Kofferraum suitcase room (boot)	Beutelratte pouch rat (opossum)	Taschenuhr bag watch (pocketwatch)	Tütensuppe bag soup (packet soup)	Sackkarre sack cart (hand truck)
Metals	Goldfisch (goldfish)	Silbermünze (silver coin)	Eisennagel (iron nail)	Kupferschale (copper bowl)	Bleistift lead pen (pencil)
Transport vehicles	Autobahn car track (motorway)	Schiffsschraube ship screw (ship's propeller)	Bootsanleger boat pier (landing pier)	Zugticket (train ticket)	Wagenheber cart jack (car jack)
Insects	Fliegenpilz fly mushroom (fly agaric)	Spinnennetz (spider web)	Ameisenhaufen ant pile (anthill)	Bienenstich bee sting (type of cake)	Wespennest (wasp's nest)
Weather	Regenwurm rain worm (lobworm)	Sonnenbrille (sunglasses)	Schneebesen snow broom (whisk)	Windpocken wind pox (chickenpox)	Nebelhorn (foghorn)
Furniture	Spiegelei mirror egg (fried egg)	Tischdecke (table cloth)	Lampenschirm (lampshade)	Sofakissen (sofa cushion)	Bettwäsche (bed linen)
Drinks	Biergarten (beer garden)	Wasserwaage water scale (bubble level)	Milchreis milk rice (rice pudding)	Kaffeefilter (coffee filter)	Sektglas sparkling wine glass (champagne glass)
Fruits	Kirschkern (cherry pit)	Apfelwein apple wine (cider)	Zitronenfalter lemon moth (brimstone)	Traubenzucker grape sugar (dextrose)	Orangensaft (orange juice)
Electronics	Telefonbuch (phone book)	Computerkabel (PC cable)	Druckerpapier printer paper (printing paper)	Radiowecker radio alarm (clock radio)	Handyhülle (mobile phone case)
Buildings	Kirchenglocke	Scheunentor	Hausnummer	Hüttenkäse	Turmfalke

	(church bells)	barn gate (barn door)	(house number)	(cottage cheese)	tower hawk (kestrel)
Spices	Knoblauchpresse (garlic crusher)	Salzgestein (salt rock)	Currywurst curry sausage (currywurst)	Pfeffermühle (pepper grinder)	Ingwertee (ginger tea)
Shapes	Linienblatt line paper (ruled paper)	Kreissäge circle saw (circular saw)	Kreuzkümmel cross caraway (cumin)	Quadratwurzel (square root)	Rautentaste hash key (pound key)
Kitchen equipment	Gabelstapler (forklift)	Ofenrohr (stovepipe)	Pfannkuchen (plancakes)	Topfpflanze (pot plant)	Löffelbiskuit spoon biscuit (ladyfinger)
Nature	Seehund sea dog (seal)	Strandkorb beach basket (beach chair)	Meerrettich sea radish (horse redish)	Flussufer river shore (riverside)	Bergbau mountain construction (mining)
Filler	Schuhsohle (show sole), Hutständer (hatstand), Gürtelschnalle (belt buckle), Hemdkragen (shirt collar), Lattenrost (slatted frame), Geigenkasten (violin case), Klavierhocker (piano stool), Trompetenärmel (trumpet sleeve), Türschlüssel (keys), Wandregal (rack), Fensterbank (windowsill), Bodenfliese (floor tile), Kaminholz (firewood), Briefmarke (stamp), Heftpflaster (plaster), Tintenfass (inkwell), Feuerzeug (lighter), Kronjuwelen (crown jewels), Mülltonne (dushbin), Klorbürste (toilet brush), Kassenbon (receipt), Ölkanne (oilcan), Tackerklammer (stapler (pin)), Pillendose (pillbox), Tattoonadel (tattoo needle), Seifenblase (soap bubble), Angelhaken (fishhook), Pappkarton (cardbox), Komposterde (compost soil), Schiefertafel (slate)				

Appendix B: Statistical data

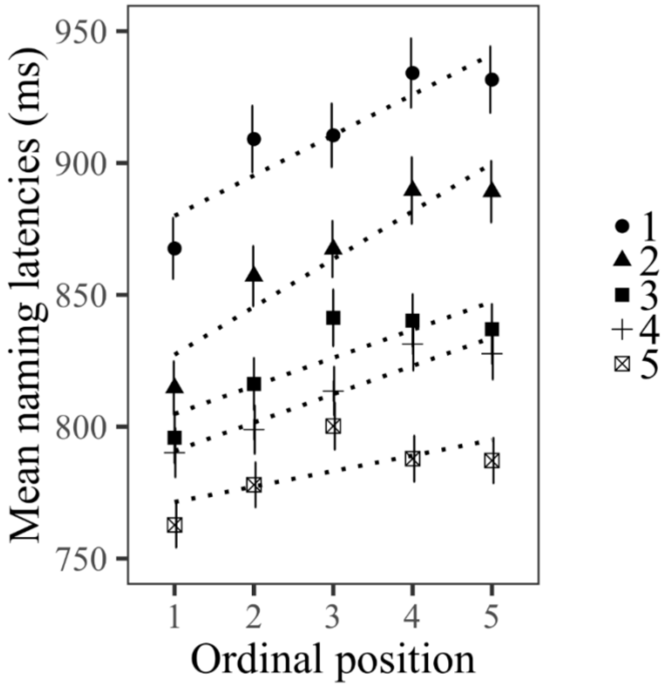

Figure 1. Mean naming latency and standard error (in milliseconds) for each ordinal position, collapsed over word type, broken down by repetition. The lines represent the slope of the linear trend of the interference effect for each repetition.

Table 1
Analysis of subcycles: Fixed-effect estimates, standard errors, t- values and p-values; estimates of the variance and standard deviations of the random effects.
-1000/RT ~ Word type*Position*Repetition + Word type*Position*Semantic similarity+ Trial + Lemma frequency + (word_type || subject)+ (word_type || cat) + (word_type || item_id)

	-1000/RT			
Predictors	*Estimates*	*std. Error*	*t-value*	*p*
(Intercept)	-1.283	0.032	-40.604	<0.001
Word type	0.023	0.058	0.393	0.696
Position in subcycle	-0.001	0.003	-0.344	0.730
Repetition	-0.096	0.005	-18.162	<0.001
Semantic similarity	0.036	0.026	1.353	0.180
Trial	0.001	0.000	10.926	<0.001
Lemma frequency	-0.068	0.015	-4.699	<0.001
Word type x Position in subcycle	-0.006	0.005	-1.132	0.258
Word type x Repetition	-0.015	0.003	-5.771	<0.001
Position in subcycle x Repetition	0.003	0.002	1.398	0.162
Word type x Semantic similarity	-0.088	0.046	-1.916	0.059
Position x Semantic similarity	0.007	0.006	1.222	0.222
Word type x Position x Repetition	-0.002	0.004	-0.642	0.521
Word type x Position x Semantic similarity	0.005	0.011	0.428	0.669
Random effects	**Variance**	**sd**		
Subject (Intercept)	0.07	0.36		
Subjects (Word type)	0.02	0.12		
Category (Intercept)	0.01	0.06		
Category (Word type)	0.01	0.03		
Item (Intercept)	0.02	0.11		
Item (Word type)	0.01	0.03		
Residuals	0.05	0.21		

Table 2
Analysis of compound targets including semantic similarity of compounds: Fixed-effect estimates, standard errors, t- values and p-values; estimates of the variance and standard deviations of the random effects.
Model: -1000/RT ~ Ordinal position * repetition + Ordinal position*Semantic similarity modifiers + Ordinal position*Semantic similarity compounds + Trial + Lemma frequency +(1 | Subject)+ (1| Category) +(1| Item)

	-1000/RT			
Predictors	*Estimates*	*std. Error*	*t-value*	*p*
(Intercept)	-1.272	0.036	-35.387	<0.001
Ordinal position	0.014	0.004	3.637	<0.001
Repetition	-0.087	0.008	-10.960	<0.001
Semantic similarity modifiers	-0.019	0.026	-0.730	0.469
Semantic similarity compounds	0.050	0.023	2.186	0.032
Trial	0.001	0.000	5.066	<0.001
Lemma frequency	-0.068	0.017	-4.016	<0.001
Ordinal position x Repetition	-0.002	0.003	-0.786	0.432
Ordinal position x Semantic similarity modifiers	-0.012	0.008	-1.601	0.109
Ordinal position x Semantic similarity compounds	-0.001	0.007	-0.085	0.932
Random effects	**Variance**	**sd**		
Subject (Intercept)	0.03	0.35		
Category (Intercept)	0.00	0.01		
Item (Intercept)	0.01	0.11		
Residuals	0.05	0.2		

Table 3
Analysis including factor order: Fixed-effect estimates, standard errors, t-values and p-values; estimates of the variance and standard deviations of the random effects.
Best fit: -1000/RT ~ Word type*Ordinal position*Order + Word type* Ordinal position *Repetition + Word type* Ordinal position *Semantic similarity + Trial +Lemma frequency + (Word type || subject)+ (Word type || category) + (Word type || Item)

	-1000/RT			
Predictors	*Estimates*	*std. Error*	*t-value*	*p*
(Intercept)	-1.283	0.032	-40.609	<0.001
Word type	0.022	0.041	0.553	0.583
Ordinal position	0.022	0.003	7.445	<0.001

Order	0.006	0.051	0.125	0.901
Repetition	-0.102	0.007	-13.732	<0.001
Semantic similarity	0.036	0.026	1.375	0.173
Trial	0.001	0.000	8.456	<0.001
Lemma frequency	-0.069	0.015	-4.731	<0.001
Word type x Ordinal position	-0.025	0.005	-4.883	<0.001
Word type x Order	0.543	0.078	6.948	<0.001
Ordinal position x Order	-0.002	0.005	-0.400	0.689
Word type x Repetition	-0.016	0.003	-5.959	<0.001
Ordinal position x Repetition	-0.006	0.002	-2.997	0.003
Word type x Semantic similarity	-0.089	0.045	-1.965	0.053
Ordinal position x Semantic similarity	0.006	0.006	1.098	0.272
Word type x Ordinal position x Order	0.014	0.010	1.309	0.190
Word type x Ordinal position x Repetition	0.006	0.004	1.732	0.083
Word type x Ordinal position x Semantic similarity	-0.035	0.011	-3.191	0.001

Random effects	**Variance**	**sd**
Subject (Intercept)	0.01	0.05
Subjects (Word type)	0.02	0.19
Category (Intercept)	0.01	0.09
Category (Word type)	0.01	0.04
Item (Intercept)	0.02	0.17
Item (Word type)	0.01	0.05
Residuals	0.05	0.23