Semantic context effects on language production in neurotypical speakers and people with aphasia

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List of Abbreviations

ATL: Anterior Temporal Lobe

CN: Continuous Naming

CSI: Cumulative Semantic Interference

MRI: Magnetic Resonance Imaging

PWI: Picture-Word Interference

SLN: Swinging Lexical Network

SOA: Stimulus Onset Asynchrony

VLSM: Voxel-based Lesion Symptom Mapping

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1 Introduction

Processing the continuous stream of perceptual inputs, human brains are eager to form increasingly large meaningful units to recover overall meaning. Such processing applies to verbal input but also to visual or acoustic objects and is paramount to our understanding of the surroundings we interact with. When we interact via language referring to an object or concept by its name, activation of semantic and categorical information is necessary to retrieve the correct lexical representation to name the object. In language production research, this process is often approximated experimentally by confrontation naming of objects usually represented by pictures. While this is largely effortless for uncompromised speakers, people with acquired lesions to the language network may show great difficulties in retrieving the correct word. This can result in non-fluent or erroneous speech production in people even with residual aphasia.

Previous research has shown that the semantic context can interfere with or facilitate naming. Taken together, the study of impaired language production in aphasia, as well as investigations of the effects of semantic context on language production, have shaped our understanding that word retrieval during naming is a process consisting of several steps (Dell et al., 1997; Levelt et al., 1999). In people with aphasia each of these steps may be selectively impaired, leading to the large variety of observed patholinguistic patterns.

In my dissertation project (summarized visually in Figure 1) I investigated novel aspects of the process of lexical selection in neurotypical speakers and in people with acquired language impairments. In my *first study* (van Scherpenberg et al., 2020), I addressed the extent to which picture naming can be inhibited through multiple semantically related word distractors in neurotypical speakers. To achieve this, I applied a novel variant of the established so-called picture-word interference paradigm (see below) and combined it with eye tracking to assess the relationship of (inhibited) lexical retrieval and semantic processing. In my *second study* (van Scherpenberg et al., 2021), I built on these findings and applied the novel paradigm in participants with acquired lesions to the language network to tap into the relationship of pathological difficulties in lexical retrieval and semantic interference.

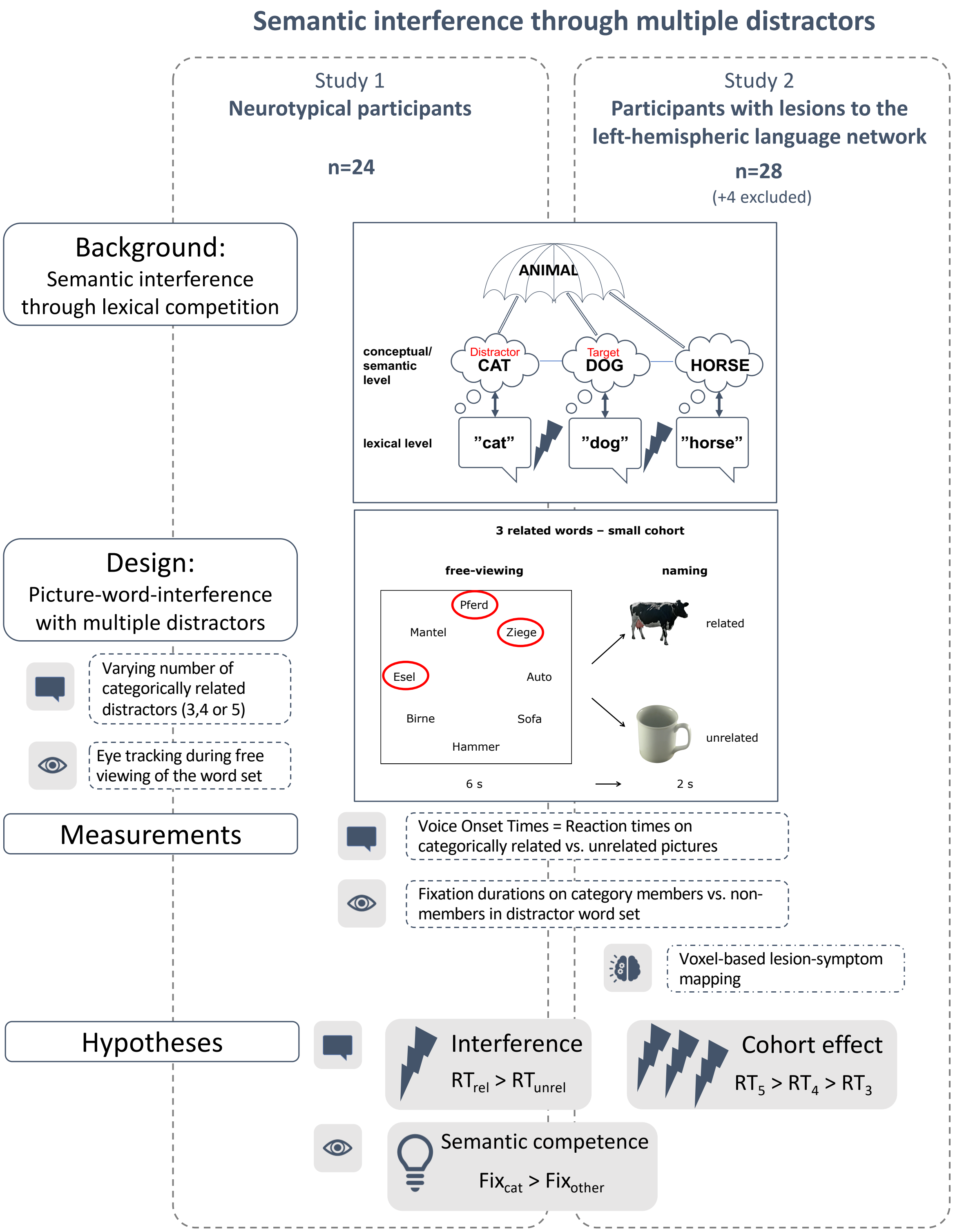

Figure 1: Summary of the dissertation project

1.1 Modelling the language production process

Previous research on neurotypical and impaired language production converges on the assumption that the process of referring to an object by its name involves several steps. Models of language production differ in the extent to which they describe these steps as uni- or bi-directional, linear and / or independent from each other. For instance, the model by Levelt et al. (1999, see Figure 2), still a prominent starting point for most theoretical accounts, assumes a linear language production process from conceptual preparation to articulation of the word. The research summarized in this dissertation focused on the first two steps of the process: the conceptual and semantic activation of the target concept, and the selection and retrieval of its lexical representation. Semantic context effects on language production arise from an interaction of these two steps, as I will explain in more detail below.

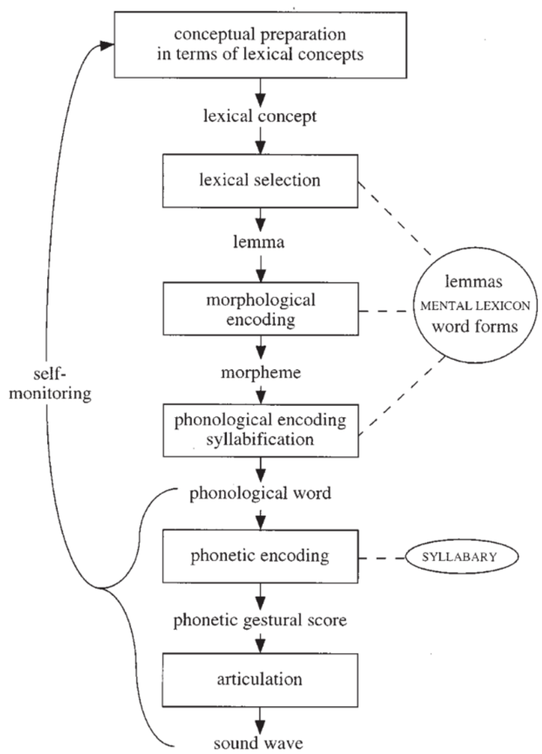

Figure 2: Levelt et al's (1999) model of language production

1.1.1 Semantic activation and priming

Upon recognition of the picture of an object, its meaning is accessed. The speaker activates different aspects of knowledge about the object, such as its colour, function, category membership and other semantic features. For example, when seeing the picture of a dog, the information HAS FUR, BARKS, IS AN ANIMAL might be activated. This step is necessary to define an object, but also to distinguish it from other, related objects (e.g. “cow”: HAS FUR, EATS GRASS, IS AN ANIMAL) (Vigliocco et al., 2004). Importantly, research has shown that semantic relationship of the context in which a picture is named influences the speed and accuracy of target naming. For example, naming has been shown to be inhibited in the presence of semantic coordinates, that is, concepts that share many semantic features and belong to the same semantic category (e.g., animals). When semantic coordinates are presented as distractor words along with the target picture (e.g., cat$_{\text{DISTRACTOR}}$ and dog$_{\text{TARGET}}$), naming is slowed down or more erroneous responses are produced when compared to the presence of distractor words unrelated to the target picture (e.g., cherry$_{\text{DISTRACTOR}}$ and dog$_{\text{TARGET}}$). This so-called *semantic interference effect* through categorically related distractor words in the *picture-word interference paradigm* (PWI) has been replicated many times in language production research (see e.g., Damian & Bowers, 2003; Glaser & Düngelhoff, 1984; Lupker, 1979; Schriefers et al., 1990; Starreveld & La Heij, 1996). However, interestingly, naming has been shown to be facilitated and faster when distractor words stand in an associative semantic relationship with the target (e.g. bone$_{\text{DISTRACTOR}}$ and dog$_{\text{TARGET}}$) (Abdel Rahman & Melinger, 2007; Alario et al., 2000; Henseler et al., 2014; Pino et al., 2021; Sailor et al., 2009). In this case, a semantically related concept seems to prime picture naming.

1.1.2 Lexical selection by competition

One explanation for the interference of categorical, but not associative distractors with target naming is offered by the lexical competition hypothesis. Upon identification and semantic activation of the target concept, when viewing the object or a graphical representation of it, its correct lexical representation must be accessed in order to proceed to morphological encoding and finally articulation of the target word (Levelt et al., 1999; Roelofs, 1992, 1997). Supporters of the lexical competition hypothesis suggest that target retrieval results from its selection amongst competing lexical alternatives (Abdel Rahman & Melinger, 2009; Caramazza, 1997; Levelt et al., 1999; Roelofs, 1992). For example, upon presentation of a categorically related distractor word (e.g., “cat”) simultaneously with the target picture (e.g., of a dog), the distractor’s lexical representation is a competitor to the target’s lexical representation (e.g., “dog”) because both are possible alternatives in the task to name the picture, as they both belong to one semantic category (e.g., animal). This provides an explanation for slowing or even erroneous choice of a lexical entry in the PWI paradigm. Having to select the correct option amongst its competitors results in the delayed naming which is observed in this paradigm. Note that when distractor and target are presented simultaneously, this is referred to as a Stimulus Onset Asynchrony (SOA) of 0. A negative SOA implies that the distractor was presented before the target (e.g., at SOA = -100: 100ms before the picture).

1.1.3 Semantic context effects and the Swinging Lexical Network

Together, interference caused by lexical competition and facilitation caused by semantic priming are two seemingly disparate effects of semantic context on language production at different levels of the language production process. Recently, the Swinging Lexical Network (SLN) model (Abdel Rahman & Melinger, 2009, 2019) offered an overarching explanation of the experimentally observed effects. These are conceived as net behavioural effects resulting from underlying processes. The model operates with two basic assumptions: (1) semantic context presented in the form of word distractors or in other modalities always induces both conceptual priming and lexical competition and the observed effect (facilitation or interference) depends on which mechanism outweighs the other. (2) Measurable semantic interference is only induced by a cohort of lexical competitors – in other words, activation from just one competitor is not enough to induce interference.

To illustrate these assumptions for the PWI paradigm, a categorically related distractor word primes the target concept through shared category nodes. At the same time, the distractor also receives activation since its lexical representation is activated upon reading it, making it a lexical competitor. However, due to spreading semantic network activation, a distractor activates not only the target, but also other members of the same semantic category. When this semantic activation spreads further to the lexical level, these activated lexical entries form a cohort of competitors and the network is "swinging" (Figure 3). In this case, lexical competition through cohort activation clearly outweighs semantic priming and interference prevails (Abdel Rahman & Melinger, 2009). Conceptual activation through distractors which are not part of the semantic category, however (e.g., semantic associates or part-whole relatives), does not activate a lexical cohort and the priming effect predominates, resulting in null effects or facilitation (Alario et al., 2000; Bloem & La Heij, 2003; Costa et al., 2005; Navarrete & Costa, 2005).

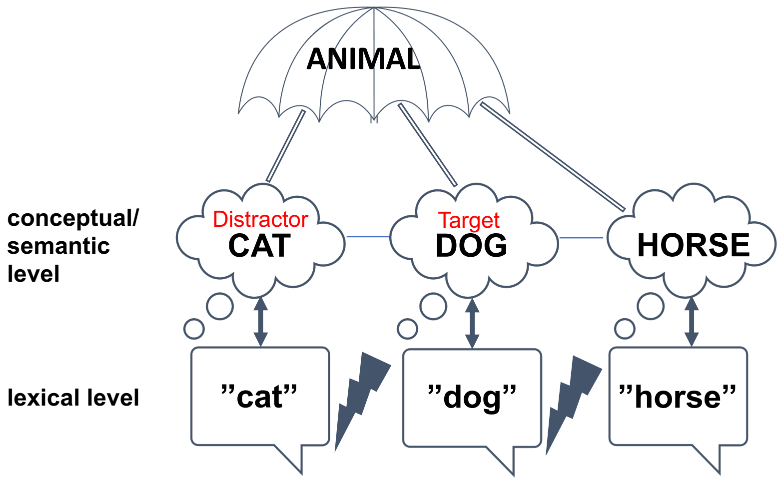

Figure 3: Cohort activation and lexical competition between categorically related concepts

1.2 Study 1 – Interference through multiple distractors

The SLN account posits that a lexical cohort of sufficient size introduces semantic interference in picture naming. According to the SLN and based on a proposal by Luce (1959), the selection of a target lexical entry depends on the sum activation of all other lexical entries. Consequently, the probability of target selection should be influenced by the number of activated items in the lexical network and their activation levels.

In the first study of my dissertation, I followed up on this assumption and hypothesized that displaying multiple word distractors instead of just one (as typical for the classical picture-word-interference paradigm) would therefore add activation to the lexical cohort. This should enhance the difficulty of retrieving the correct target representation from amongst its lexical competitors and should result in a stronger interference effect. We therefore devised a paradigm in which multiple words were displayed at the same time in a circular arrangement. The paradigm was implemented in a group of 24 young, healthy adults (see Study 1 in Chapter 2.1 below). In each trial, a variable number (3, 4 or 5) of these words were categorically related to each other (e.g., sheep, cow, horse from the category animals), while each of the remaining words (i.e. 5, 4 or 3) stemmed from a different semantic category and were unrelated to each other. While participants viewed this set of words, their eye movements were tracked to investigate which of the words they fixated for how long. After an exploration time of 6 s, the words disappeared, and the target picture was displayed. It either belonged to the same category of the semantically related distractor words (related condition) or stemmed from an entirely different category (unrelated condition). Participants were asked to name this picture as quickly and accurately as possible. Thereby, we were able to assess (1) the PWI effect in the related naming condition, (2) the influence of a varying number of multiple word distractors on the interference effect and (3) explicit fixation on and processing of the semantic category through eye tracking.

1.3 Eye movements and explicit semantic processing

The set-up of our new variant of the PWI paradigm described above allowed us to investigate and control how participants process the semantic context they were perceiving in the distractor word set, by measuring their eye movements during inspection time. Previous research combining eye tracking with a semantic task, such as in the visual world paradigm (Faria et al., 2018; Huettig et al., 2011; Huettig & Hartsuiker, 2008; Seckin et al., 2016; Yee et al., 2009; Yee & Sedivy, 2006) suggests that participants' eye movements reveal their explicit semantic processing abilities or, in other words, their "semantic competence". For example, in paradigms performed with people with Primary Progressive Aphasia, these participants fixated on semantically unrelated objects (foils) more often and longer when compared to neurotypical controls, indicating impaired semantic memory abilities and difficulties to establish the semantic relationships between concepts (Faria et al., 2018; Seckin et al., 2016).

Assuming that neurotypical young adults are semantically competent, in the novel paradigm introduced in my dissertation project they should spend longer time fixating on words which they have acknowledged to belong to the same category, compared to the unrelated words. Therefore, analysing fixation times can be used to investigate the semantic "competence" of the participants in each trial and their *explicit* acknowledgement and processing of the semantic category.

Importantly, in Study 2 of my dissertation (see 1.5 and 2.2 below) I investigated the question whether explicit acknowledgement of the categorically related distractor words (indicated through longer fixations on those) is necessary to induce an interference effect. Here we implemented the novel PWI paradigm described above in participants with chronic lesions in the left hemispheric language network and aphasia symptoms, assessing its feasibility and contributing to our understanding of semantic context effects also in this population.

1.4 Semantic context effects in people with acquired language impairments

In contrast to the abundance of evidence in neurotypical speakers, fewer studies so far have gathered information on PWI in people with aphasia. This does not reflect the fact that effects of semantic context and lexical inhibition assessed with this paradigm have great potential to shed light on the impairment of the different processing steps involved in picture naming. In addition to reaction times, naming errors allow insights into the dynamics of word production. Moreover, knowledge about the patients' brain damage permits to correlate their behaviour in the naming task with their lesion pattern to gain information about neural underpinnings of the language production process. As a clinical perspective such research may lay a foundation for theory-based intervention protocols.

Previous research has revealed inconsistent results. Wilshire et al. (2007) report facilitation instead of interference effects for an anomic patient in an auditory PWI paradigm at SOA = 0. This pattern stands in contrast to the effect normally observed in neurotypical participants. The authors hypothesize that due to impaired and therefore slowed semantic processing, lexical retrieval is not initiated in time for the distractor word to exert its inhibitory effect. Instead, the priming effect of the semantically related concept prevails. On a group level, Piai and Knight (2017) investigated semantic interference in neurotypical participants and two patient groups with circumscribed lesions – one group mainly in frontal, the other largely in temporal areas. They observed a robust interference effect in both reaction times and error rates only in the group with lesions to the left-lateral temporal cortex. In contrast, most recently, Pino et al. (2021) reported robust interference effects in the PWI paradigm in a large group of participants with lesions to the language network, both in reaction times and errors, at SOA = -100. Beyond the behavioral results this study shed light on the involvement of lesioned brain areas in naming latencies and semantic interference by applying voxel-based lesion-symptom mapping (VLSM) analyses. The authors report a correlation between an increased semantic interference effect and lesions in the inferior frontal gyrus. Moreover, decreased overall reaction times in picture naming, but not the interference effect, correlated with lesions in the middle temporal gyrus.

Overall, these findings add proof to the observation that semantic context effects are variable and depend on timing, type of impairment and lesion site.

1.5 Study 2 – Multi-word interference and semantic competence in participants with acquired lesions to the language network

In the second study of my dissertation project, I addressed the question how a lesion to the left hemispheric language network affects two specific aspects of semantic context effects. To this end 28 participants with chronic but mild aphasia after left-hemispheric circumscribed chronic brain lesion performed the same multi-word interference task combined with eye tracking, as introduced in Study 1. The study targeted three questions. First, we addressed the feasibility of conducting this rather complex language production task in participants with significant word retrieval issues. Second, we investigated how a semantic context consisting of a cohort of categorically related competitors affected picture naming latencies in this group. Making use of the structural MRI scans available for all participants, we moreover correlated this behavioral measure with the participants' lesions (the VLSM approach). This allowed us to gain information about the neural underpinnings of lexical retrieval and distractor inhibition. Third, tracking the participants' eye movements while they viewed the distractor set, we hypothesized that, like in the neurotypical group, preferential fixation to category members within the word set would indicate "semantic competence". However, this ability may be dependent on the type of impairment and lesion site. Previously, the Anterior Temporal Lobe (ATL) has been suggested as a semantic "hub" involved in conceptual processing (Mesulam et al., 2013; Pobric et al., 2007). Therefore, lesions in this area may be correlated with difficulty in processing the category membership within the cohort. This would be in line with evidence from participants with Semantic Dementia, which show similar semantic impairments and focal lesions dominantly in the ATL.

Building on these hypotheses, we assessed the relationship between explicit acknowledgement of a categorical relationship, that is preferential fixation to category members, and the semantic interference effect. According to the SLN model (Abdel Rahman & Melinger, 2009, 2019) and related accounts (see 1.1. above), semantic interference results from pre-activation of a cohort of category members which compete with each other during lexical selection. We therefore addressed the question whether *explicit* processing of categorically related words is necessary to activate the category to a degree where its members become competitors during target naming. Although there is evidence that semantic activation is implicit and automatic once a threshold is reached (see, e.g., Piai et al. (2012), and see Howard et al. (2006) for evidence of implicit semantic processing from a different naming paradigm), this mechanism may be altered in participants with an impaired semantic network (Pisoni et al., 2012).

1.6 Semantic context effects beyond picture-word interference

In addition to the PWI paradigm, which was the basis for the studies I conducted for my doctoral project, research on semantic context effects in language production has relied on other experimental paradigms. Those most frequently used are the blocked cyclic naming paradigm and the continuous naming (CN) paradigm. In both paradigms, pictures are named consecutively, while the semantic context is manipulated without written or auditory distractors. The CN paradigm was the focus of two other studies which I conducted to investigate semantic context effects once more in a cohort of participants with lesions to the language network, and in an online setting. These studies have been submitted or are in preparation for submission. In the CN paradigm, several exemplars of semantic categories are named within a seemingly unrelated sequence of pictures. Naming has been shown to become slower across ordinal positions of pictures within their semantic category, resulting in the so-called cumulative semantic interference (CSI) effect (Howard et al., 2006). This effect is considered to stem from the fact that repeated access to a semantic category cumulatively increases the number of lexical competitors even when unrelated pictures are named in between (Abdel Rahman & Melinger, 2019; Belke, 2013; Belke & Stielow, 2013; Oppenheim et al., 2010). Evidence for CSI in participants with aphasia is still sparse (see Harvey et al. (2019) for evidence on naming errors only). We addressed this open question in a collaboration project (Pino, van Scherpenberg et al., in preparation). Participants with lesions to the language network completed the CN paradigm, but also, in a second session, the classical PWI paradigm. This allowed us, for the first time, to compare cumulative and distractor-induced semantic interference within one cohort of participants, while taking into account the role of language impairments on picture naming.

In addition, we recently replicated the CSI effect in a web-based setting, by testing participants remotely in two online experiments through their web browsers (Stark, van Scherpenberg, et al., 2021). In overt spoken responses acquired through the participants' microphones (experiment 1) as well as typewritten responses acquired via their keyboards (experiment 2), the CSI effect proved to be robust. Moreover, typewritten responses can be preprocessed automatically, which drastically reduces the workload. They are therefore a reliable and efficient alternative to the spoken response modality. Our successful replication thus offers new possibilities for conducting reaction-time sensitive language production research online with large and diverse populations. It also eases the access to testing participants with impairments which hinder in-person experimental sessions.

2 Published studies

2.1 A novel multi-word paradigm to investigate semantic context effects in language production

PLOS ONE

RESEARCH ARTICLE

A novel multi-word paradigm for investigating semantic context effects in language production

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Abstract

Semantic context modulates precision and speed of language production. Using different experimental designs including the Picture-Word-Interference (PWI) paradigm, it has consistently been shown that categorically related distractor words (e.g., cat) inhibit retrieval of the target picture name (dog). Here we introduce a novel variant of the PWI paradigm in which we present 8 words prior to a to be named target picture. Within this set, the number of words categorically related was varied between 3 and 5, and the picture to be named was either related or unrelated to the respective category. To disentangle interacting effects of semantic context we combined different naming paradigms manipulating the number of competitors and assessing the effect of repeated naming instances. Evaluating processing of the cohort by eye-tracking provided us with a metric of the (implicit) recognition of the semantic cohort. Results replicate the interference effect in that overall naming of pictures categorically related to the distractor set was slower compared to unrelated pictures. However, interference did not increase with increasing number of distractors. Tracking this effect across naming repetitions, we found that interference is prominent at the first naming instance of every picture only, whereby it is stable across distractor conditions, but dissipates across the experiment. Regarding eye-tracking our data show that participants fixated longer on semantically related items, indicating the identification of the lexico-semantic cohort. Our findings confirm the validity of the novel paradigm and indicate that besides interference during first exposure, repeated exposure to the semantic context may facilitate picture naming and counteract lexical interference.

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Introduction

The way speakers select appropriate words in a given context has been the subject of research for many decades. It has been shown that both linguistic and task-related factors play key roles in determining which word a healthy speaker will select during language production. Models

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to describe uncompromised language production mostly agree in assuming four steps in the word retrieval process most commonly investigated by picture naming [e.g., 1,2]: [1] (Visual) object identification, [2] access to an object's semantic representation, [3] retrieval of the corresponding lexical representation and [4] retrieval of the phonological word form. Notably, the semantic context of the target to be named has been found to influence speed and accuracy of target word production. To explore this finding further the first aim of the current study was to investigate whether naming speed can be modulated by changing the intensity of semantic context activation. This was achieved by modulating the number of items creating the semantic context. The second aim was to assess how speakers explore the visually presented semantic context and whether processing intensity influences naming latencies.

Semantic context effects on target word production have been shown using a number of variations of three classical paradigms: Picture Word Interference (PWI) [distractor word competing with picture; e.g., 3–7], blocked-cyclic naming [semantically homogeneous/heterogeneous blocks; e.g., 8–11] and continuous naming [semantically related interspersed with unrelated items, 12]. The converging observation is that semantic context can influence lexical-semantic processing and lexical retrieval in opposite directions (i.e. both interference and facilitation). This has led to different theories explaining how semantic context interacts with the target, one major debate being at which steps during word production it does so. The "Swinging Lexical Network" (SLN) account by Abdel Rahman et al. [13,14] agrees with many other theories that lexical selection for word production is characterized by competition between lexical entries. In addition, it assumes that a distractor primes the target on the conceptual level, because both share semantic features (e.g., *cat*, *cow*, *pig*, all share the meaning "animal with four legs"). The trade-off between this conceptual facilitation and lexical competition determines whether lexical selection will be inhibited or facilitated. Abdel Rahman et al. [13] argue for a selection mechanism like the Luce ratio [15]. The selection of a target lemma is dependent on the sum activation of all other lemmas. Consequently, the number of activated items in the lexical network and their activation levels should influence the probability of target lemma selection. When many competitors are activated, the target stands in a one-to-many competition with them. The SLN model therefore predicts that only when a cohort of inter-related items induces overall activation in the lexical network, this will surpass conceptual facilitation, and an interference effect will arise. Additional members of the lexical cohort should therefore lead to more activation within the network, and increase interference with the target word [13,14].

So far, this mechanism has been studied mostly indirectly by manipulating the proximity of semantically related items within the naming context. For example, a study by Rabovsky et al. [16] showed that an object is more likely to co-activate mutually related concepts and their lexical representations, the more semantic features it shares with other concepts [17]. Here, pictures with higher endogenous semantic neighborhood densities were named more slowly and less accurately, because they activated a larger cohort of lexical competitors resulting in slower lexical selection.

Moreover, the semantic context paradigms mentioned above have shown that the activation strength of competing items is another important factor. For instance, closely semantically related items that share more semantic features (e.g., *donkey*, *horse*, *cow* vs. *donkey*, *trout*, *owl*), lead to slower naming than semantically distant items. These graded semantic effects have been found for all major paradigms: PWI [18,19], blocked cyclic naming [20], and continuous naming [21]. The findings reveal that semantic interference can be modulated by changing the structure of the semantic context in which a picture is named. One extreme case is that facilitation as opposed to interference is elicited, usually when the semantic relationship between target and (distractor) context is not categorical but associative (e.g. *donkey—stable*, *hay*, *farmer*).

In the framework of the SLN model the explanation is that no interrelated lexical cohort is activated and target and distractor (simultaneously presented or previously named) stand in a one-to-one competitive relationship with each other. In this case the facilitation on the conceptual activation level outweighs interference, and target selection is faster [13,22,23]. Alternative explanations have claimed semantic facilitation to be the default effect, with semantic interference occurring only at post-lexical processing steps, where task-relevant (i.e. semantically related) responses to pictures have to be actively excluded [response exclusion hypothesis; 24–26].

In the present study we focus on categorical semantic relations and investigate whether manipulating the extent of lexical activation within a lexical cohort modulates inhibition on subsequent picture naming. Using a set of closely related entries of a number of lexical cohorts the activation strength per item can be assumed to be largely homogeneous. Using these sets we parametrically change the number of distractors to investigate, whether this has a direct influence on the amount of semantic interference. In this vein a previous study [27] found a significantly increased interference effect in the PWI paradigm when two instead of one semantically related words were shown as distractors. In the present study the semantic context is created by presenting a total of 8 words. Critically, three to five of these words are categorically related, forming the lexical cohort. We measure the influence of cohort size on reaction times when naming a picture presented *after* the word array. The picture to be named is either categorically related or unrelated to the lexical cohort. We hypothesize that reaction times for a related picture will be slower the more related words were presented, because a more strongly activated lexical cohort should lead to more competition between lexical entries, resulting in longer naming latencies.

The extent to which presenting a number of written words before naming pictures can influence picture naming speed has been investigated in previous research [28–31]. However, in these experiments, words were presented consecutively and had to be overtly read out aloud. Moreover, the findings are partially contradictory. For example, Navarrete et al. [28 (Experiment 3), 29] found no transfer of interference from word to picture naming within one semantic category, whereas Vitkovitch et al. [30,31] did report semantic interference for naming pictures after having named semantically related words. We here investigate how simultaneous presentation and lexical activation by reading (not producing) the words impact on the processing of the semantic relationships between the words and consecutive naming of un/related items.

To study and control how participants process the semantic context we additionally measure their eye movements while they view the distractor words. We proceed from the rationale that eye tracking can be used to investigate the semantic 'competence' of viewers. This assumption rests on paradigms performed in people with Primary Progressive Aphasia (PPA) and neurotypical controls. Suggesting impaired semantic memory abilities, participants suffering from PPA [32,33] fixated on semantically unrelated objects (foils) more often and longer when compared to neurotypical controls, likely indicating difficulties to establish the semantic relationships between concepts. Here we hypothesize that the neurotypical young adults are semantically competent and should hence fixate on words longer which they have recognized to belong to the same category, when compared to the unrelated words. Thus, analysis of fixation times was used to investigate the semantic 'competence' of the participants in each trial. Additionally, we can use this measure to estimate the extent to which they activate the lexical cohort. According to the eye-mind hypothesis [34,35], readers' gaze durations are immediately linked to what they are processing. That is, words that are fixated longer are also processed longer. We therefore predict that the longer participants fixate on related words belonging to the lexical cohort, the more activity will spread to this cohort and induce stronger competition resulting in inhibition on target selection.

Apart from the nature and extent of semantic relation it should be noted that previous research has shown interference and facilitation to differ as a function of timing (at the trial level) and repetition (i.e. across the experiment).

Timing in the PWI paradigm has been shown to greatly affect naming speed: Prominently, the interval between a distractor word and target (the stimulus onset asynchrony, SOA) influences the polarity of the context effect [5,36–38]. Manipulating the SOA systematically with different time intervals, Zhang et al. [36] demonstrated that a semantic interference effect from categorically related word distractors only occurred at an SOA of -100ms before, or of 0ms, that is simultaneously to, target onset. At longer negative SOAs (-1000 to -400ms), the effect transformed into semantic facilitation–using the same stimulus materials. Similarly Python et al. [38] find facilitation from categorically and associatively related distractor words at an SOA of -400ms. These findings indicate that at longer SOAs, conceptual priming outweighs lexical competition. We will address this issue in more detail in the Discussion. Moreover, semantic context effects may change when a specific picture or a category is *repeatedly* named. For example, in the blocked cyclic naming paradigm's first presentation cycle, a homogeneous block often does not lead to longer but shorter naming latencies when compared to the first heterogeneous block [9,22,39–42]. Interference from homogenous context appears only from the second cycle onwards, and has been reported to grow with each repeated block of related pictures [growth effect; e.g., 9,11; but see 8, and 39 (Experiment 1 and 2a)]. In continuous naming, reaction times increase across ordinal position of the target pictures within their semantic category [e.g., 8,12,28,43]. These cumulative or growth effects are explained by incremental learning as proposed by Becker et al. [44] and Damian and Als [9] and further developed in a computational model (the "Dark Side Model") by Oppenheim et al. [45]. It is assumed that connections between a concept's features and its lexical representation are strengthened by repeated access during target naming. This results in faster activation of the item and therefore reduced naming latencies on future naming occasions (repetition priming). However, enhanced activation makes the already named item a stronger competitor for its related concepts, while connections to semantic features shared between the target and related concepts from the same semantic category are weakened (the "dark side" of repetition priming). Therefore, access to a related concept's lexical representation is slower. Conceivably a combination of both factors leads to cumulative interference for items from one semantic category in picture naming settings such as the continuous or blocked naming paradigms [28,45,46].

In contrast to these paradigms, to our knowledge, for a PWI paradigm changes across naming repetitions have been formally addressed only in one recent study [47]. Using an auditory PWI design, interference effects are reported to be largely stable across naming repetitions of the same pictures with phonological distractors. This stands in contrast to the other paradigms mentioned above, and systematic conclusions about the stability of the interference effect in PWI paradigms can only be tentative at present.

The repetition- or sequence-effect changing the contribution of interference and facilitation across the experiment is complemented by findings of studies looking at small-scale changes of the effects in response time distributions. Two recent studies have shown that when dividing the participants' rank-ordered response times into deciles, the interference effect is driven by the slowest decile and small or absent in the fastest 10% of response times [48,49]. Both studies explain findings by attentional processes which influence the strength of distractor processing: When attention is low, the distractor might be processed more intensely while the ability to inhibit its interfering effect might be reduced, and therefore reaction times are longer. A high level of attention, however, mediates the interference effect and reaction times become faster.

All in all, research on the change of interference and facilitation effects as a function of timing (SOA) manipulations, over repeated naming-instances and within response time distributions, shows that the effects are sensitive to timing modulations and can sometimes even occur in one and the same task. The present study therefore addresses this issue by including the repetition factor in the analyses. We aim to explore whether the typical interference effect–replicated many times for the PWI paradigm–can be influenced by trial progression as well. Repeated access to the same category members might facilitate target retrieval across several naming occasions. Alternatively, it might lead to increased competition within the category's lexical cohort and therefore to cumulative interference as the experiment progresses. This process may be influenced by changes in attention across trials. Finally, a long SOA, necessary to allow for full processing of each of the eight distractor words, might affect the semantic interference effect as well.

Methods

Participants

24 young adults (15 females), aged 18–32 years (M = 24.5, SD = 3.8), participated in this study in return for monetary compensation of €9 per hour. All participants were right-handed, had no history of neurological or other relevant diseases and had normal or corrected-to-normal vision. The number of participants was determined through the randomization lists needed to fully randomize all stimuli and trial orders (see below).

Experimental procedures were approved by the Institutional Review Board of the University of Leipzig, Germany, in accordance with the Declaration of Helsinki, and written informed consent was obtained from all participants.

Material

We used a variation of the picture-word interference (PWI) approach in which a picture has to be named after the presentation of a distractor word. Different form 'classical' PWI-designs, an array of 8 distractor words was presented simultaneously, before the picture to be named appeared. Thereby the number of related and unrelated distractor words could be parametrically varied.

The stimulus set consisted of 42 items from 7 semantic categories. The chosen items were closely related as members of subcategories of superordinate categories (*superordinate categories* in brackets): seating (*furniture*), street-vehicles (*vehicles*), face parts (*body-parts*), fruits (*food*), upper body clothing (*clothes*), hoofed animals (*animals*), and carpenter's tools (*tools*); see S1 Appendix).

The frequency of occurrence as a target picture to be named and as a member of the distractor word set was equal across items. Within the sets of eight words a varying number [3, 4 or 5] belonged to the same semantic category, representing the lexical cohort. The remaining unrelated items [i.e. 5, 4 or 3] each stemmed from one of the remaining semantic categories. To control for potential confounding effects all words used in the paradigm have a highly similar frequency: mean = 12.29, sd = 1.88, according to the Leipzig Corpora Collection [50]. Moreover, potential item-based effects are strongly attenuated by the fact that randomization was complete across conditions: Each target picture was named once as a related or unrelated target in each of the three distractor conditions, that is: following the presentation of three, four or five related words within the lexical cohort, whereby the cohort was always randomly arranged from one of the 7 categories. With the 7 semantic categories with 6 items each and each picture being named 6 times in total, this led to a total number of 252 trials. Out of these, 84 trials each were attributed to one experimental block.

The word stimuli were presented in white Arial font, size 40, on a black screen. All pictures were colored photographs taken form the Bank of Standardized Stimuli [51], stock image databases or creative commons sources. They were scaled to 5.8 x 5.8 cm (300x300 pixels, 5.5° of visual angle at a distance of 60cm between the viewer's eyes and the screen). The material was selected avoiding strong visual similarities between members of small categories, e.g. "apple" and "grapes" for fruits. A complete list of the stimuli is given in the supplementary materials.

Apparatus

The stimuli were presented using the Psychophysics Toolbox extension [52] for MATLAB (2017a, MathWorks, Inc.) on a Lenovo ThinkPad T420 laptop (14" monitor, 1600x900 pixels resolution). Eye movements were recorded from both eyes using a Tobii X2-60 eye tracker with a 60 Hertz sampling rate. Voice responses were recorded using a Blue Yeti USB microphone.

Design and procedure

The variation of the number of related words in the distractor set results in a 2x3 design with picture TYPE (related vs unrelated) and SIZE of lexical cohort [3, 4 or 5] as within-participants factors. Twelve randomized lists were created with the constraints that target pictures were separated by a minimum of two other items and that each target appeared once with a related and once as an unrelated distractor set in each block. Across each list, the participants therefore named each item six times. The lists were duplicated and randomly assigned to the 24 participants.

At the start of each session participants were instructed about the experimental procedure and were then seated in a dimly lit, sound-proof room in front of the laptop and eye tracker with a distance of approximately 60 cm to the screen. A chin rest was used to minimize head movements and improve eye-tracking data quality.

Prior to the main experiment participants were familiarized with the pictures: each picture was presented once with the written name centered on a black screen, which participants read out aloud. The familiarization phase was self-paced and the order of picture presentation within this phase was randomized individually for each participant. No participant had difficulty recognizing and naming the pictures. After familiarization the eye tracker was calibrated according to a 5-point calibration procedure. This was followed by three practice trials, after which any remaining questions were addressed by the experimenter.

The experimental sessions consisted of three blocks with 84 trials each. Between blocks, participants were able to take a break. Each trial started with a fixation cross centered on a black screen (0.5s), directly followed by a set of eight words presented in a circle around the center of the screen for 6s (see Fig 1 for a typical trial procedure). Participants were told that a minimum of three of the eight words were related to each other and they were instructed to inspect the word set freely. During the viewing part, participants' eye movements were recorded by a Tobii X2-60 eye tracker. Directly after, the distractor words disappeared, and the target picture was presented for 2s. Participants were instructed to name the picture as quickly and accurately as possible. After an inter-trial interval of 0.5s, the next trial started automatically. Each trial lasted for 9s, resulting in a total experiment time of around 38 minutes, not including breaks.

Analysis

Reaction times

The voice onset times were detected using Chronset [53], and checked manually using Praat [54]. The onsets were determined at the start of each word, excluding stuttering or "uhms". 3.14% of all trials had to be excluded from further analyses. 2.36% were trials in which

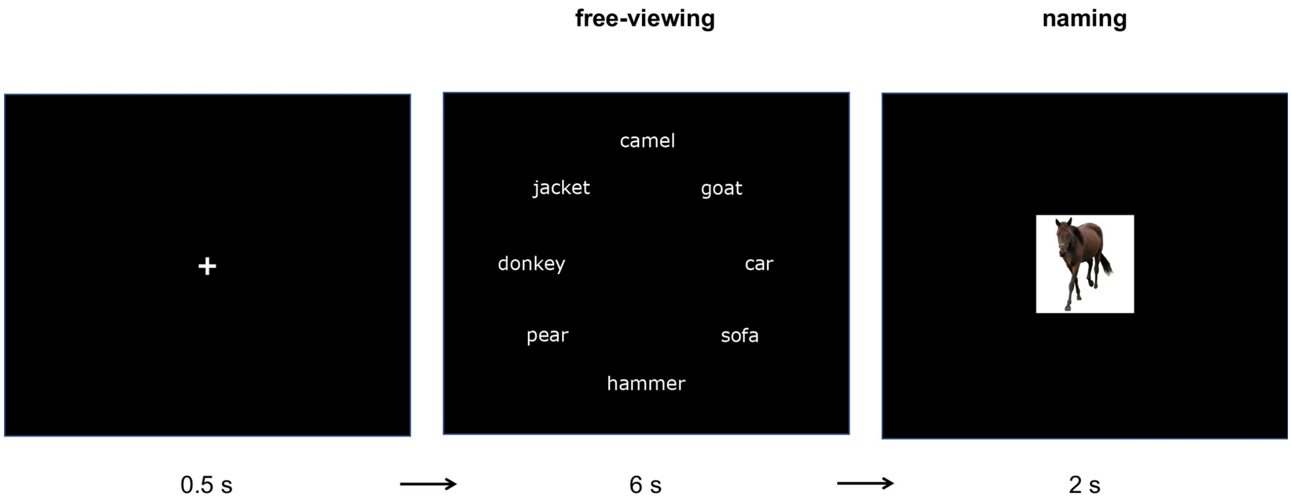

Fig 1. Exemplary procedure of a trial in which the word set contains a lexical cohort of three items from the semantic category "hoofed animals" and this lexical cohort is related to the target picture. In the actual experiment, the words were presented in German.

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participants did not respond at all or the recording was cut off, whereas only 0.78% were due to false responses. Errors were therefore not analyzed any further.

Eye tracking data

From the raw data samples fixations and saccades were detected using the GazePath algorithm [55] on the mean x- and y-coordinates of the left and right eye. Heatmaps of the fixations were plotted to establish large enough but not overlapping Areas of Interest (AoI) for each word in the circular word set. These were then defined as rectangles of 270x170 pixels around each word. Trials where GazePath had failed to detect any fixations were excluded from analysis. This led to a total data loss of 1.87% for the eye tracking data. Combining data loss from reaction time and eye tracking data, a total of 5% had to be removed from data analysis.

Statistical analysis

All statistical analyses were performed using R version 3.6.1 [56]. Generalized Linear mixed effect models (GLMM) were run with random slopes for subjects and items, using the lme4 package in R for linear mixed models [version 1.1–21;, 57], and *p* values were determined using the package lmerTest [58]. This allowed us to investigate the relationship between voice onset times and picture type, number of related items in the word set, and fixation durations on related items for the group, while taking individual and stimulus-related variance into account. We always started with a model including the maximal random structure. When convergence errors occurred, we reduced the model by running principal component analyses on the random-effects variance-covariance estimates and correlation parameters until the random structure was supported and convergence achieved [59–61]. As suggested by Lo et al. [62], reaction time data can be best modelled using GLMMs to approximate normal distribution of the data without the need to transform the raw data using inverse or log transformations. For the present analyses we chose a Gamma distribution with identity link, to best match the right-skewedness of the raw data with a long tail in the slow RTs, and also in the fixation durations distribution (see S2 Appendix).

Table 1. Mean RTs in milliseconds and standard error of the means for each naming condition.

Distractor set size	3		4		5		total	
Picture type	**related**	**unrelated**	**related**	**unrelated**	**related**	**unrelated**	**related**	**unrelated**
Mean RTs in ms	847.06	833.13	829.82	827.82	835.99	821.41	837.69	827.44
SE	6.05	6.15	6.13	6.03	6.17	5.86	4.56	4.48
Interference	13.93		2.00		14.58		10.25	

SEM = Standard Error of the Mean. Values are adjusted for within-participant designs following [63].

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Results

Reaction times

Raw naming latencies for picture type in total and in each distractor set condition are given in Table 1.

To statistically confirm the differences in naming latencies between picture types (related or unrelated to the distractor set), distractor set sizes [3,4 or 5 related words], and naming repetitions, we used generalized linear mixed models (GLMM). We report estimates, standard errors, t- and p-values in the text and tables for complex models. All full models and model outcomes can be found in S2 Appendix (Tables B1 and B2).

Relationship between picture TYPE and distractor set SIZE. We first turn to the analysis of the global effects on naming latencies, that is the main effect of picture TYPE, the main effect of distractor set SIZE, as well as the interaction between the two. In this first model, picture type and set size were both contrast-coded using sliding difference contrasts, which compute differences between adjacent factor levels. This allows to retrieve pairwise comparisons directly from the model output, instead of running post-hoc analyses (e.g., related vs unrelated picture type, 4 vs 3 set size; note, however, that we can only compare n-1 factor levels in each model). The final model that converged included a fully specified random structure (by-subject and by-item random intercepts and random slopes for all fixed effects plus interactions), excluding correlation parameters. It revealed a significant semantic interference effect, in that naming a related picture was slower than naming an unrelated picture (TYPE; estimate = 10.94, $SE = 4.00$, $t = 2.73$, $p = 0.006$). The main effect of set SIZE was significant for 4 compared to 3 distractor words (estimate = -11.33, $SE = 4.13$, $t = -2.74$, $p = 0.006$) and for 5 compared to 3 distractor words (estimate = -11.79, $SE = 4.05$, $t = -2.91$, $p = 0.004$). This indicates that naming was significantly faster for 5 or 4 distractor words compared to only 3 distractor words. The interaction between picture TYPE and set SIZE was significant for 4 vs 3 distractor words (estimate = -11.98, $SE = 5.21$, $t = -2.3$, $p = 0.021$) but not for 5 vs 3 words (estimate = 0.46, $SE = 5.87$, $t = 0.08$, $p = 0.938$). These main effects are summarized in Fig 2.

To investigate this interaction further we fitted another model, where the fixed effect of picture type was nested within the levels of distractor set size [64]. The random structure was again fully specified, without correlation parameters. The results show that interference was only significant at a set size of 3 (estimate = 14.01, $SE = 5.11$, $t = 2.71$, $p = 0.006$) and 5 (estimate = 15.63, $SE = 5.51$, $t = 2.83$, $p = 0.005$) but not 4 distractor words (estimate = 2.75, $SE = 5.02$, $t = 0.55$, $p = 0.584$), in line with the interaction effects in the first model. These results show that contrary to our hypothesis, interference did not increase for additional distractor words.

Relationship between picture TYPE, distractor set SIZE, and naming REPETITION. We furthermore fitted a GLMM to track the development of the interference effect and the effect of set size across naming repetitions. Here picture repetition was added as a continuous fixed

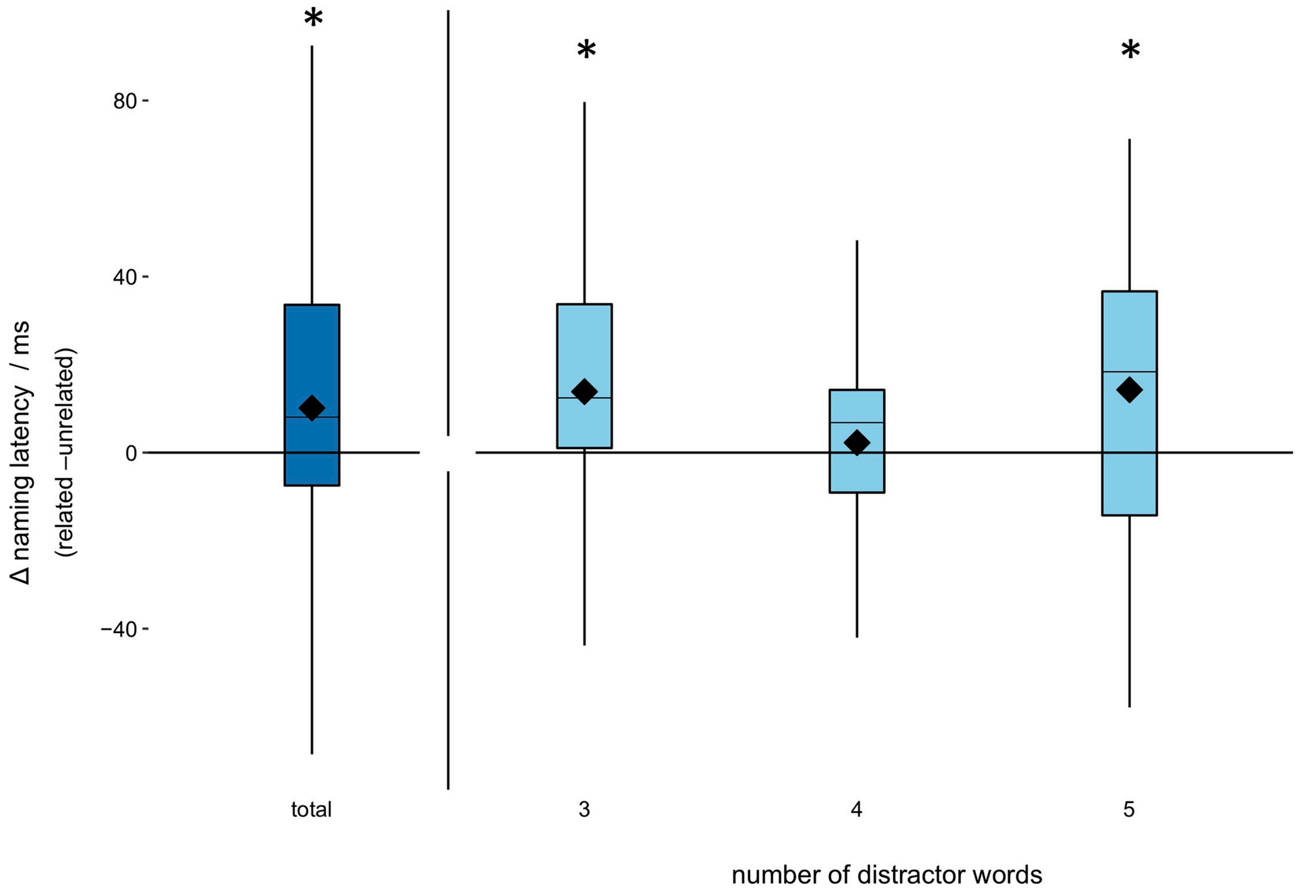

Fig 2. Interference effect in total and across number of distractor words. Total interference was significant at ~10ms. For 3 and 5 distractor words, interference was significant at ~15ms. There was no interference effect for 4 distractor words. Boxplots show mean, median, upper and lower quartiles and range.

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effect and z-transformed. From the random structure correlation parameters as well as one contrast of the factor set size were removed to achieve convergence. As can be seen in Table 2, with this additional factor in the model, the main effect of picture type remained significant. However, it interacted (marginally) significantly with naming repetition, showing that the interference effect decreased across naming repetitions. When removing this interaction effect from the random structure for Item and Subject, the effect became highly significant (estimate = -9.50, *SE* = 2.94, *t* = -3.23, *p* = 0.001). This means that participants as well as items varied with regard to this effect. Nevertheless, log likelihood tests showed that the more complex model fit the data better (logLik $\Delta X^2(2) = 22.08$, p <0.001). We therefore report the more complex model. Overall RTs decreased by 39 ms on average for each additional target picture occurrence. The main effects of set size remained significant as well and did not interact with picture repetition (all t < 0.82, all p >0.414). Finally, the three-way interaction between picture TYPE, set SIZE and picture REPETITION was not significant (all t < 1.58, p > 0.114).

As can be seen in Fig 3, the interference effect is strongest at the first naming instance across all conditions. This was confirmed in a final (random intercept) model looking at the interaction of picture type and set size for the first naming instance. The effect of picture type was significant at ~44ms (estimate = 43.83, *SE* = 9.01, *t* = 4.86, *p* < 0.001) and the interactions with

Table 2. GLMM for the effect of picture type and set size across naming repetitions.

Term	Estimate	SE	t	p
Intercept	870.81	5.83	149.48	<0.001
Picture type: rel-unrel [a]	10.33	5.22	1.98	0.048
Set size: 4–3	-10.33	4.07	-2.54	0.011
Set size: 5–3	-10.80	3.91	-2.76	0.006
Pic repetition	-39.29	6.24	-6.29	<0.001
Pic type * set size: 4–3	-11.87	3.98	-2.98	0.003
Pic type * set size: 5–3	0.48	5.57	0.09	0.932
Pic type * pic repetition	-7.87	4.25	-1.85	0.064
Set size: 4–3 * pic repetition	-4.50	5.50	-0.82	0.414
Set size: 5–3 * pic repetition	1.54	4.04	0.38	0.703
Pic type * set size: 4–3* pic repetition	7.86	4.97	1.58	0.114
Pic type * set size: 5–3* pic repetition	-7.23	5.86	-1.23	0.217

[a] henceforth "pic type".

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set size were not significant (all $t < 1.51$, $p > 0.132$). This confirms a stable interference effect of around 44ms for all distractor conditions at the first naming instance.

Eye tracking measures

To investigate viewing times of the mutually related and unrelated words in the word set, fixation durations were summed up on each AoI, yielding a total viewing time for each word in each trial. For each trial, total viewing time recorded by the eye-tracker was ~4100 ms on average (i.e. ~1900ms participants did not fixate on any of the AoIs or data were not recorded). The measure can be assumed to depend on data quality (e.g. blinks) and attentional resources. Fig 4 shows the mean viewing times for each related and unrelated word across all trials and participants, and for each lexical cohort condition [3, 4 or 5 mutually related words out of 8 words in total in each trial]. If there was no bias in fixating to members vs. non-members of the cohort, each word should be fixated for $1/8^{th}$ of the total fixation time. The measures show that participants fixated longer on members than non-members, and therefore indicate the participant's categorization skills of semantically related and unrelated words in each word set.

The descriptive results were statistically confirmed by a GLMM with word type (related or unrelated) and distractor set size (i.e., 3, 4 or 5 related words) as fixed effects and a fully specified random structure.

Factor level contrasts showed that related words were fixated about 112ms longer than unrelated words (estimate = 114.44, SE = 16.05, $t = 7.13$, $p < 0.001$) and that the more related words there were, the shorter each word was fixated (4–3: estimate = -18.16, SE = 5.25, $t = -3.46$, $p = 0.001$; 5–3: estimate = -28.34, SE = 6.31, $t = -4.49$, $p < 0.001$). This did not depend on the type of word (related, i.e. part of the categorical distractor set, v.s. unrelated) that was fixated (no interaction effect, all $t < 0.56$, all $p > 0.574$). For details see S3 Appendix, Table C1.

Combined RT and eye tracking analysis

A final hypothesis concerned the relationship between fixation durations on the related words in the lexical cohort, and naming latencies for the consecutively named picture. We hypothesized that the longer participants fixated on the categorical distractor words within the cohort, the longer the RTs on naming a related picture would be. This relationship was analyzed by

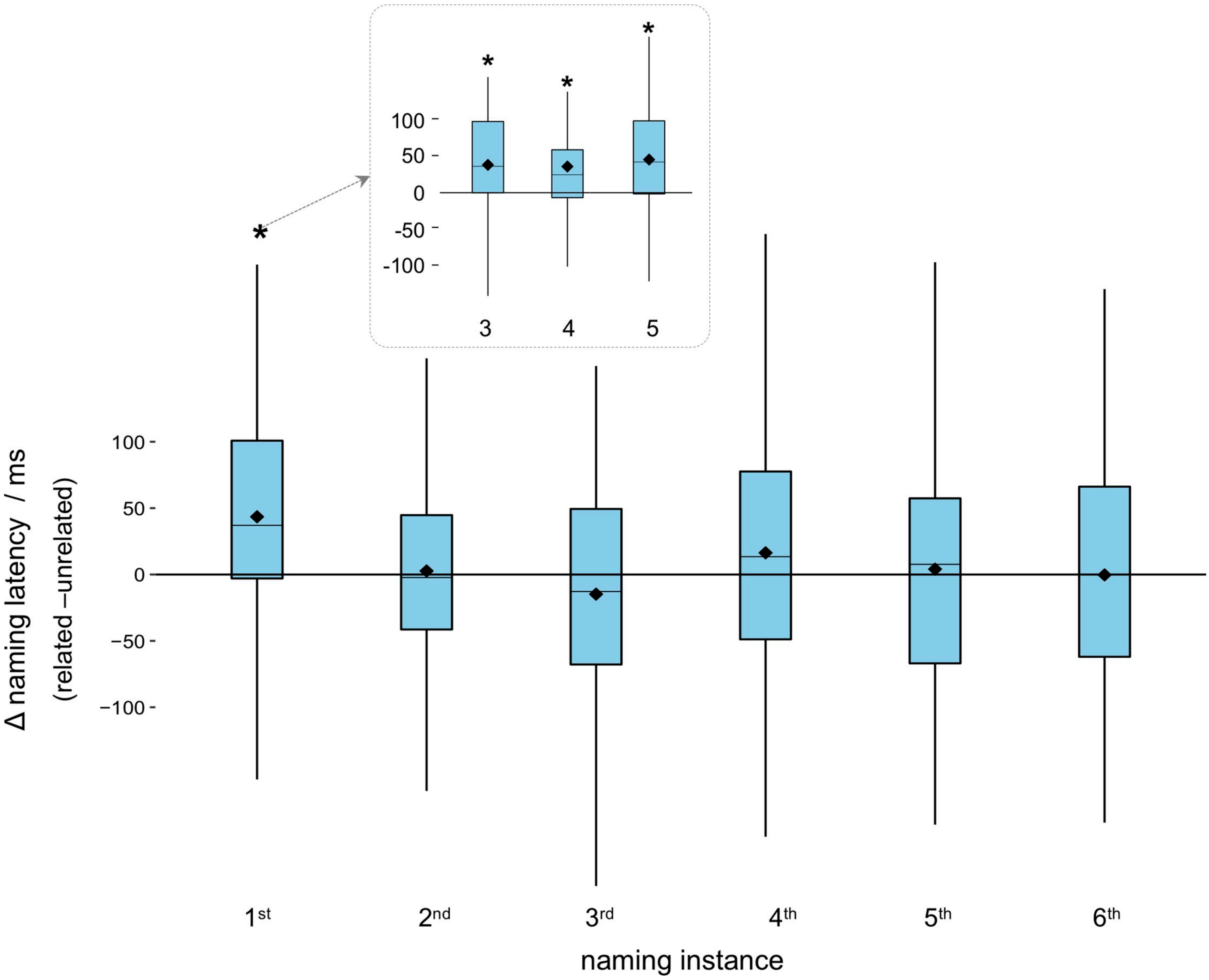

Fig 3. Interference effect across naming instances (each picture was named 6 times in the related and unrelated conditions over the course of the experiment). Interference was highly significant at the first naming instance and disappeared for the following repetitions. Note that the significant effect for the first naming instance was significant for all distractor conditions (inset). Boxplots show mean, median upper and lower quartiles and range.

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another LMM adding fixation durations as a covariate (z-transformed) and a maximal random structure without correlation parameters. According to this model taking fixation durations into account, the interference effect in naming latencies remained marginally significant (estimate = 9.76, SE = 5.68, t = 1.72, p = 0.086). However, fixation durations did not influence naming latencies significantly (main effect of fixation durations: estimate = 2.54, SE = 2.58, t = 0.98, p = 0.327). Fixation durations also did not interact with picture type or set size (all t <. 1.56, all p > 0.118). For details see S4 Appendix, Table D1.

This matches the results of Pearson's correlations between fixation durations and reaction times for each participant. The weak correlation became significant for 5 participants, but the average correlation coefficient was 0.

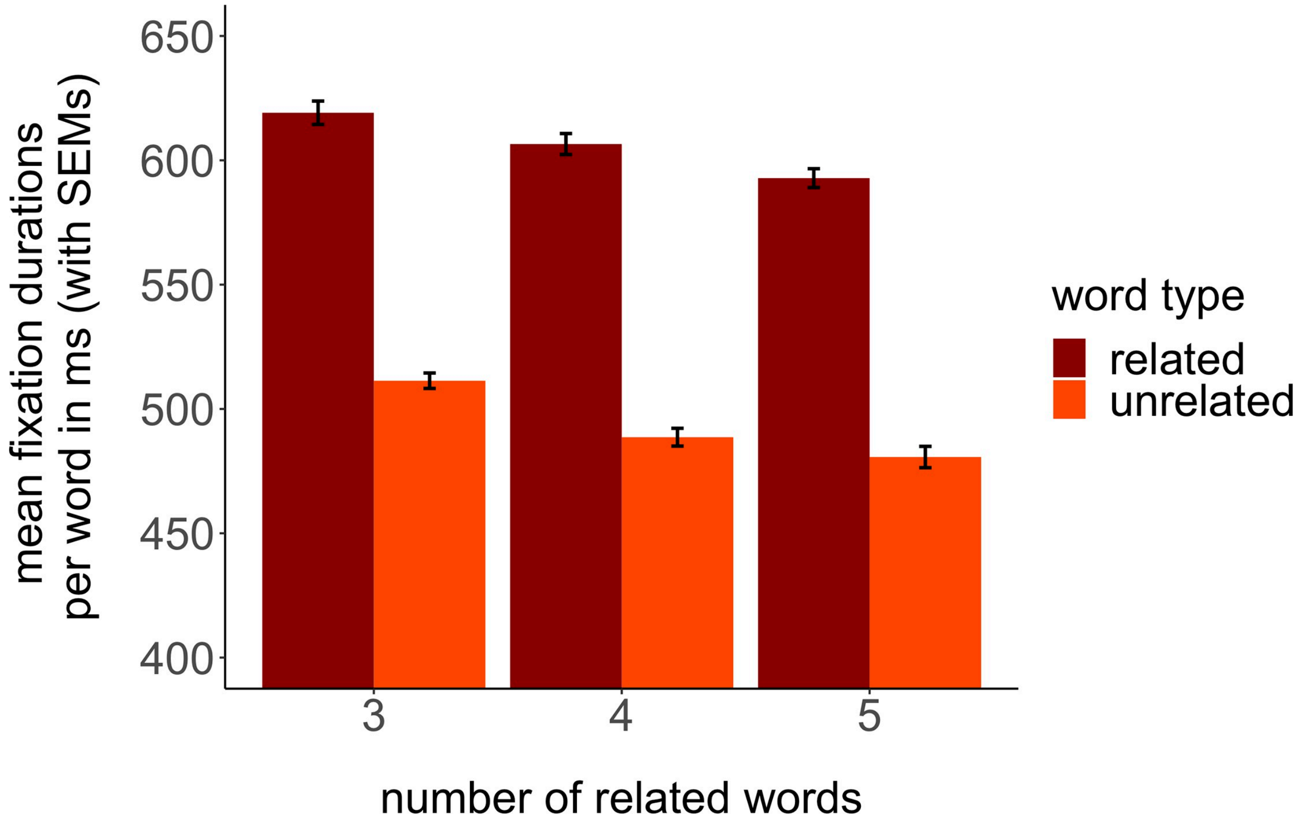

Fig 4. Mean relative fixation durations (with SEMs) for each word as part of the distractor word set.

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Discussion

In this study, we introduce a novel variation of the picture-word-interference (PWI) paradigm to investigate whether and how semantic interference effects through categorical distractors can be modulated. Consistently it has been shown that for the PWI paradigm categorically related single word distractors elicit slower naming responses for pictures from the same when compared to a different semantic category [see, e.g., 3,5,13,65]. This interference effect has been associated with the activation of a lexical cohort of related category members inducing competition during lexical selection and thereby delayed target word retrieval [13]. Besides lexical cohort effects, semantic relation between distractor words and the target word to be produced can also lead to facilitation. In that case the competition-induced slowing may be counteracted by effects likely arising at the conceptual level (i.e. 'animal with 4 legs'). To further elucidate the complex interplay between such opposing effects during picture naming we here address three questions using a variation of the PWI paradigm: First of all we address effects of the *size* of the lexical cohort. Some evidence exists that activation is driven by category size, such that for larger categories (e.g., animals) more members/competitors can be activated when compared to smaller, narrower categories (e.g., insects); this relies on studies investigating semantic neighborhood density effects on picture naming [16,66]. Recent research, however, has also shown that interference increases for category members that are more closely related, leading to smaller numbers of exemplars [e.g., hoofed animals, 18,21]. In the present study, we therefore manipulate lexical cohort activation in a more controlled way by changing the number of word distractors forming the semantic naming context for picture naming. While doing so, we kept the semantic categories in the stimulus set narrow, using categories that had elicited high interference effects in Rose et al. [18,21]. A second issue addressed in the present study is the question whether and how semantic *cohort recognition* shapes semantic context effects. The prediction here is not straight forward: while semantic knowledge on the cohort is mandatory for the interference effect, the search for exemplars of the cohort in the visual word set may activate a conceptual, rather than a purely lexical search. While the latter should increase interference, the use of conceptual semantics is predicted to facilitate lexical access. To tap into this intriguing question, we used eye tracking to assess the individual processing of the semantic context. (iii) Finally, we address the question how effects of semantic context unfold across trials. This is of interest since continuous or blocked-cyclic naming paradigms suggest a build-up of interference with repeated exposure, while PWI-paradigms typically do not report sequence effects.

Beyond the more general inquiry into how semantic context shapes picture naming, we specifically ask whether an increased number of categorically related words in a PWI paradigm inhibits or facilitates retrieval of a target picture name and whether this effect changes over repeated instances of naming. Analyzing fixation times, we additionally assess rather than assume semantic 'competence' for the different conditions.

In brief, our findings confirm an interference effect when words categorically related to the picture to be named are presented prior to the picture. This effect, however, disappears with repeated naming and the duration of fixation on the semantically related distractor words does not predict naming latency. Most notably the effect of the number of semantically related words in the distractor set is contrary to predictions based on a simple interference account. With an increasing number of categorically related words in the distractor set, semantic interference did not increase further.

The increase in naming latency when words presented prior to the picture are categorically related replicates previous results using semantic PWI. The interference effect is generally interpreted to show that reading the words activates lexical representations connected through one category node, making them strong enough competitors to inhibit target selection when the target was part of the same semantic category [see e.g., 67,68, on the time course of this process]. Replicating this finding in our novel paradigm indicates that interference of categorically related words with the naming of a picture is robust even if timing of the individual trial and the number of distractors is substantially altered. The overall effect of around 10 ms is smaller than found in typical PWI paradigms, but is statistically significant across all participants and trials, even when taking participant and stimulus variation into account using mixed effects modeling.

Notably, however, the development of this effect over repetitions reveals that a net-interference effect occurred only at the first out of six naming instances for each target picture for which it was much larger (~44 ms), irrespective of the number of categorically related items in the distractor set. The effect dissipates across the remaining target presentations, and overall reaction times decrease by about 120 ms from first to last naming instance of each target picture, suggesting an increase in facilitatory mechanisms, neutralizing interference effects. Such a reduction of the interference effect evidenced by naming latencies when comparing repeated naming instances has not been demonstrated for PWI paradigms [and see 47 for evidence that interference remains stable across naming repetitions of the same picture]. It also stands in contrast to findings from the blocked cyclic or continuous naming paradigms, where reaction times increase across trials [cumulative interference, e.g., 12], or interference only appears from the second presentation cycle onwards and afterwards remains stable or even increases slightly [8,9]. Note, however, that this sort of cumulative interference results from the repetition of *categories*, not single *items*. Nevertheless, our findings also contrast with alternative explanations of the origins of semantic interference, specifically the response-exclusion hypothesis [24]. This theory posits that through frequent exposure, task-relevant responses (e.g. names of pictures from the same semantic category) need to be actively excluded from an articulatory output-buffer resulting in delayed naming. In our paradigm, these task-relevant items would include previously named pictures, and previously fixated words that were part of a category word set. But as we discuss in more detail below, our results show that indeed frequent exposure to the material leads to *faster* naming, thus making an explanation of an effortful and therefore inhibitory monitoring mechanism unlikely.

The most noteworthy finding of the current study pertains to the effect of distractor set size: Contrary to our hypothesis, interference did not increase from 3 to 4 or 5 distractor words that were semantically related to the picture, but was equally strong (~15 ms) for 3 and 5 distractor words. Interestingly, when 4 distractors were part of the word set, naming was not interfered at all. In sum, regarding the extent of activation modulated by cohort size of semantically distractors we have to reject the hypothesis that a larger number of distractor words induces more competition on target word retrieval. This will be further discussed below.

Using eye-tracking, a third relevant finding relates to how participants process the semantic context provided by the distractor words: average fixation time on categorically related words was significantly longer compared to that on the remaining, unrelated words. The finding is notable in two ways: firstly, it confirms that neurotypical participants implicitly categorize words without specific instruction to do so. Moreover, the analysis of the eye-tracking data allowed for correlating fixation time on the semantically related exemplars in the distractor word set with naming latencies for pictures from the respective semantic category. Contrary to the assumption that longer and thereby more intense processing might lead to larger interference, the correlation was around zero for all participants. Hence, we find no indication that processing distractor words longer increases interference. If longer fixation elicits stronger lexical activation an increase in naming latency would be expected. Our null results indicate that some facilitatory effect counteracts such a purely lexical competition effect.

The fact that we find no evidence for the expected increase in the interference effect for naming latencies with an increasing number of distractor words requires discussion. A closer look at distractor conditions across naming repetitions revealed that this global result was influenced by an interaction with repetition. At the first naming instance, there was equally strong interference for all distractor conditions of around 44 ms. For all future naming instances however, interference disappeared or even turned into facilitation (= faster naming latencies for related compared to unrelated pictures). It should be noted that across the 252 trials the overall 42 'items' appeared 54 times (3 times as related, 3 times as unrelated pictures to be named and additionally 24 times as related, 24 times as unrelated distractor words). We argue that the very substantial effect of overall familiarization with the set of items (latency decrease of 120 ms over the course of the experiment) is not dependent on the number of related distractor words and holds for related and unrelated conditions.

A long stimulus onset asynchrony (SOA) and a strong familiarization with the stimulus set, both novel features of our paradigm, will have improved prediction of the target item and promoted a rather conceptual than purely lexical activation of category members. As opposed to typical single-word PWI paradigms, in our novel paradigm a negative stimulus onset asynchrony (SOA) of 6 s was used, which is much longer than in the typical single-distractor-word paradigms. Indeed, previous studies have shown that SOAs of -1000 ms or -400 ms led to facilitation rather than semantic interference for categorical distractor words presented prior to the picture [36,38]. We used the long SOA to ensure that each word, especially from the categorically related distractor words, was fixated and processed. On average participants fixated ~500 ms on each word belonging to the respective lexical cohort in the distractor set. Our results show that even with this long SOA, substantial semantic interference was elicited at the first naming instance. However, we suggest that, together with the cumulative exposure to the stimuli, this long SOA enhanced the implicit analysis of conceptual features of the lexical cohort, counteracting lexical competition. This conceptual analysis is also reflected by reduced fixation durations per word when more categorically related words were presented, and is consistent with the SLN account [13,14], in which priming on the conceptual level leads to facilitation of lexical retrieval. We therefore propose that a complex interplay between lexical interference and semantic priming effects is causal for our findings, whereby frequent exposure to the stimulus material elicits a facilitative effect on naming latencies, counteracting interference.

Outlook and implications for future research

The paradigm we have introduced in this study provides important information on the nature of picture-word interference and the processing of semantic context. Results suggest that a larger number of distractors not necessarily increases interference, even though previous research had suggested this outcome [27]. Long SOAs and frequent repetition of the stimulus material are candidate factors to lead to increased facilitation abolishing the initially robust interference effect. Furthermore, more evidence is needed to understand the relationship between semantic competence and naming latencies. In the present study, participants' semantic competence was unimpaired, and this was reflected by their ability to categorize the mutually related words in the word set. So far it is unclear how impaired semantic competence interacts with the semantic interference effect. Research on the language disorders in participants with semantic memory deficits such semantic variant Primary Progressive Aphasia (svPPA) has indicated continuing loss of semantic features as the underlying mechanism to progressive naming impairments [69–72]. This might lead to the inability to distinguish categorically related and unrelated members of the word set, and therefore to reduced or absent interference effects. The combination of our variation of the PWI paradigm with eye tracking therefore seems an apt tool to examine this phenomenon in clinical populations with (e.g. svPPA) and without (e.g. Broca's Aphasia) impairments of the semantic system.

Conclusion

In the current study we put forward a new paradigm to investigate influences of semantic context on word retrieval. We stipulated that semantic interference effects consistently found for classical PWI paradigms could be modulated in a variation of the paradigm. Here, instead of one distractor word, several distractors were presented at once, in form of a circle. This allowed us to examine the processing intensity of semantic context and parametric manipulations of the number of distractor words from on semantic category. We have demonstrated that multiple distractor words from one semantic category elicit interference–similar to that in classical one-word interference paradigms but that this effect is present only the first time a picture is presented, where it is independent of distractor set size. It then dissipates across repetitions, mediated by facilitative processes leading to faster lexical access. Moreover, interference did not increase for a larger cohort of distractor words. These findings suggest a complex interaction between activation on the lexical and conceptual processing level, which depends on lexical cohort size as well as frequency of exposure to the semantic context across repetitions within the experiment.

Supporting information

S1 Fig. Quantile-quantile plots showing distribution of RTs. Panel A: raw RTs, panel B: RTs with gamma distribution.
(TIFF)

S2 Fig. Naming latencies (raw means and SEMs) across naming instances (each picture was named 6 times in the related and unrelated conditions over the course of the experiment).
(EPS)

S1 Appendix. Stimuli.
(DOCX)

S2 Appendix. Naming latencies.
(DOCX)

S3 Appendix. Fixation durations.
(DOCX)

S4 Appendix. Combined analysis of reaction times and fixation durations.
(DOCX)

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2.2 Semantic interference through multiple distractors in picture naming in people with aphasia

Semantic Interference through Multiple Distractors in Picture Naming in People with Aphasia

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Abstract

■ When we refer to an object or concept by its name, activation of semantic and categorical information is necessary to retrieve the correct lexical representation. Whereas in neurotypical individuals it is well established that semantic context can interfere with or facilitate lexical retrieval, these effects are much less studied in people with lesions to the language network and impairment at different steps of lexical-semantic processing. Here, we applied a novel picture naming paradigm, where multiple categorically related and unrelated words were presented as distractors before a to-be-named target picture. Using eye tracking, we investigated preferential fixation on the cohort members versus nonmembers. Thereby, we can judge the impact of explicit acknowledgment of the category and its effect on semantic interference. We found that, in contrast to neurotypical participants [van Scherpenberg, C., Abdel Rahman, R., & Obrig, H. A novel multiword paradigm for investigating semantic context effects in language production. *PLoS One*, *15*, e0230439, 2020], participants suffering from mild to moderate aphasia did not show a fixation preference on category members but still showed a large interference effect of ~35 msec, confirming the implicit mechanism of categorical interference. However, preferential fixation on the categorically related cohort words correlated with clinical tests regarding nonverbal semantic abilities and integrity of the anterior temporal lobe. This highlights the role of supramodal semantics for explicit recognition of a semantic category, while semantic interference is triggered if the threshold of lexical cohort activation is reached. Confirming psycholinguistic evidence, the demonstration of a large and persistent interference effect through implicit lexico-semantic activation is important to understand deficits in people with a lesion in thelanguage network, potentially relevant for individualized intervention aiming at improving naming skills. ■

INTRODUCTION

Impaired word retrieval is a hallmark of nonfluent language production in people with aphasia (PWA). Such impairment can surface through search behavior, slower and erroneous speech (e.g., in the form of semantic paraphasias, the substitution of a target word by a semantically related word; Schwartz, 2014), or complete failure to produce certain words (anomia; Goodglass & Wingfield, 1997; Kohn & Goodglass, 1985). In psycholinguistic and neurolinguistic research, the analysis of specific deficits has shaped our understanding that word retrieval is a process consisting of several steps. In PWA, each of these steps may be selectively impaired, leading to the observed patholinguistic patterns (Levelt, Roelofs, & Meyer, 1999; Dell, Schwartz, Martin, Saffran, & Gagnon, 1997). If an object (e.g., sheep) is to be named, it is assumed that through perceptual and conceptual processes, the target is recognized and its meaning is accessed. The process includes three major steps: (i) activation of semantic features that define the item, including category membership (ANIMAL), visual (e.g., IS WHITE), or functional (e.g., PRODUCES WOOL) features (e.g., Vigliocco, Vinson, Lewis, & Garrett, 2004; Dell et al., 1997); (ii) retrieval of the object's name from the mental lexicon ("sheep"); and finally, (iii) access to the phonological representation of the target word [ʃiːp] followed by its articulatory realization.

Empirical research on both neurotypical and language-impaired populations has shown that accuracy and speed of naming vary if the respective processing levels are manipulated. For example, presenting the picture along with words phonologically or orthographically related to the target (e.g., $sheep_{PICTURE}$ and $sheet_{WORD}$) leads to facilitated and faster target naming (e.g., Abdel Rahman & Melinger, 2008; Meyer & Schriefers, 1991). This suggests phonological context to speed up the encoding of the phonological representation of the target word. In contrast, presenting context words that are semantically related to the target picture can have inhibitory effects on picture naming. In the picture–word–interference paradigm, a categorically related distractor word reduces picture naming latencies and increases error rates (e.g., Starreveld & La Heij, 1996, 2017; Wheeldon & Monsell,

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1994; Schriefers, Meyer, & Levelt, 1990; Glaser & Düngelhoff, 1984). This effect, termed "semantic interference effect," has been examined regarding the timing between distractor and target onset, the closeness of the semantic relation, and has been shown for written and auditory presentation of the distractor. Beyond the many facets of manipulation, it stands as robust evidence for the assumption that semantic context influences language production (Bürki, Elbuy, Madec, & Vasishth, 2020; de Zubicaray & Piai, 2019).

Evidence on picture–word–interference in PWA is still sparse but has great potential to shed light on the impairment of the different processing steps involved in picture naming. In an auditory picture–word interference paradigm with one anomic patient, Wilshire, Keall, Stuart, and O'Donnell (2007) report significant semantic facilitation when target and distractor are presented simultaneously (SOA = 0), whereas neurotypical participants show interference at this SOA. Notably, the anomic patient showed a trend towards semantic interference, which was only observed when the distractor was presented after the target picture onset (i.e., SOAs of +200 or +400 msec). Semantic interference effects are assumed to happen at the lexical selection stage through lexical competition, whereas priming or facilitation occurs at the conceptual level (Bloem & La Heij, 2003; Damian & Bowers, 2003; Roelofs, 1992). Therefore, the authors assume that the patient's semantic processing abilities are slowed down, prolonging the activation phase of the target's semantic representation. Thereby, at SOA = 0 msec, the distractor word would act on the pathologically prolonged semantic activation phase, not completed because of slowing. When semantic activation of the target is completed at later SOAs (+200/+400 msec), the distractor would interfere with the delayed lexical retrieval step effecting a semantic interference effect. The example demonstrates that deviations from the pattern in neurotypical participants because of lesions to the language network impair naming at specific processing steps. Indeed, a later set of studies examining picture–word–interference in participants with aphasia describe different results. Hashimoto and Thompson (2010) found significant semantic interference in RTs at SOAs = −300 and 0, with slightly bigger effect sizes but an otherwise similar pattern compared to age-matched controls. Pino, Mädebach, Jescheniak, Regenbrecht, and Obrig (2021) also report significant semantic interference for categorically related compared to unrelated distractor words in a group of 32 stroke patients (both in RTs and errors, at SOA = −100). Interference correlated with lesions to the inferior frontal cortex (IFG). Piai and Knight (2018) likewise report significant semantic interference affecting RTs and errors at SOA = 0 for a subgroup of participants with aphasia in their study. Interestingly, the subgroup largely had lesions in the left lateral-temporal cortex. Whereas the effect in RTs was similar to that of controls, this patient subgroup showed a bigger interference effect in accuracy, with significantly larger error rates for semantically related compared to unrelated distractors. According to these studies, the pattern of neurotypical participants and those with aphasia seems qualitatively comparable. Because of language production impairments in PWA, the effect shows more clearly in error rates, typically very low in neurotypical cohorts. In summary, studies in PWA support a differential impairment pattern depending on timing, semantic processing abilities, and lesion site. Although this prevents straightforward conclusions about semantic context effects in PWA, it offers a unique opportunity to study specific aspects of lexical retrieval.

In the current study, we ask how a lesion to the left-hemispheric language network alters two specific aspects of semantic context effects. To this end, we invited participants with chronic but mild aphasia after left-hemispheric circumscribed chronic brain lesion to perform a novel multiword interference paradigm previously established in neurotypical young speakers (aged 18–32 years; van Scherpenberg, Abdel Rahman, & Obrig, 2020). Naming abilities, assessed through VOT and errors, were complemented by a measure of semantic processing of the lexical cohort using eye tracking. To account for the expected large interindividual differences, we ran linear mixed models to analyze our results. Moreover, we correlated the variance of individual performance in the experiment with individual neuropsychological test scores and with individual lesion pattern.

The paradigm (introduced in van Scherpenberg et al., 2020) combines an assessment of "semantic competence" using eye tracking with a measure of lexico-semantic processing through picture naming speed and accuracy in the presence of multiple categorically related distractor words. This allows for investigating semantic and lexical processes both separately and in relation to each other. Using a circular display of eight distractor words, of which three to five belonged to one category whereas the remainder was semantically unrelated, we hypothesized that longer fixation on members of one semantic category will indicate semantic competence. This assumption rests on our finding in neurotypical, young participants using the identical paradigm. However, in people suffering from semantic dementia, it has been shown that, with increasing loss of semantic knowledge, participants spend more time fixating on unrelated foils compared to neurotypical participants with intact semantics (Faria, Race, Kim, & Hillis, 2018; Seckin et al., 2016). The task used in that study was a word-to-object matching task, also called "visual world paradigm" (Huettig, Rommers, & Meyer, 2011). Hence, impairment at the semantic processing level increases the difficulty in distinguishing between semantically related and unrelated items. In aphasia, evidence from the visual world eye tracking paradigm suggests that the participants were equally distracted from semantic competitors when having to point to the correct target picture, as were neurotypical controls (Yee, Blumstein, & Sedivy, 2008;

Experiment 1). This finding speaks for largely preserved conceptual activation of semantic relatives in typical[1] aphasia. Interestingly, phonological onset similarity disclosed differences between PWA and controls: When the distractors presented in the picture set contained competitors whose semantic relative shared the same onset as the target, neurotypical controls were more likely to fixate on a picture of an object semantically related than on an onset competitor of the target (e.g., *ham*mock$_{\text{TARGET}}$ and nail$_{\text{DISTRACTOR}}$, via *ham*mer). Whereas PWA with a Wernicke-type aphasia showed a similar semantic onset competition effect, participants with Broca's aphasia did not (Yee et al., 2008; Experiment 3). This indicates that the dynamics of lexical activation are differentially impaired in different aphasia subtypes and are reflected in fixation preference.

The combined eye tracking and picture naming paradigm used in this study allows us to investigate in how far interference in naming depends on the processing of a semantic relationship. A common explanation for the semantic interference effect through distractor words is a tradeoff between more short-lasting conceptual facilitation and longer-lasting lexical competition (Bloem, van den Boogaard, & La Heij, 2004). Although a categorically related distractor may prime the activation of the target through shared category nodes, when it comes to lexical selection, these co-activated lexical representations compete with each other, outweigh facilitation, and therefore delay retrieval (e.g., Abdel Rahman & Melinger, 2009, 2019; Melinger & Abdel Rahman, 2013; La Heij, Kuipers, & Starreveld, 2006; Wheeldon & Monsell, 1994). This competition account assumes interference is assumed to occur at the lexical selection step of the language production process.

In our paradigm, fixation on the categorically related distractor words should pre-activate the lexical cohort. Pre-activated potential lexical competitors should, in turn, hamper the selection of the lexical representation of the target picture resulting in a semantic interference effect commonly observed with single word distractors. However, if participants less efficiently distinguish between category members and nonmembers in the word set, they may not exhibit a strong semantic interference effect, because the category members did elicit strong enough activation to reach the threshold for lexical cohort activation. It follows that lexical competition and the interference effect should be smaller. In the following, we will refer to the "acknowledgment" of a semantic relationship between the distractor words, reflected by preferential fixation, as *explicit semantic processing*. Alternatively, if interference is preserved although participants show no preferential fixation of the category members, results would confirm the notion that interference is not critically dependent on the acknowledgment of the semantic cohort. This would be in line with the idea that implicit, automatic semantic activation beyond a certain threshold suffices. Evidence supporting this assumption comes from the continuous naming paradigm (Howard, Nickels, Coltheart, & Cole-Virtue, 2006), where seemingly randomly presented pictures still induce interference during naming, even when unrelated pictures are named in between. Here, cumulative interference is induced despite the absence of explicit awareness of the categorical relationship. Measuring the fixation preference while reading the words therefore provides a measure of the dynamics of semantic content processing of distractor words. Regarding the issue of implicit lexical cohort activation versus explicit acknowledgment of the respective category, we may highlight two other aspects of our paradigm: (i) Neurotypical participants did not show an effect of the number of categorically related distractor words; that is, three, four, or five related words in the distractor set elicited similarly sized interference effects. This additionally speaks for the notion that activation of lexical cohort members is largely implicit once a threshold is reached. However, in people with lesions in the lexico-semantic network, the threshold for and level of lexical cohort activation may be altered (Pino et al., 2021; Pisoni, Papagno, & Cattaneo, 2012). The current study provides information on whether lesions in specific hubs of the network modulate the automaticity of the interference effect. (ii) Participants in this and the previous studies were neither instructed to find out about the category nor was such a search of benefit for performance. The instruction was to name the ensuing target picture as fast and accurately as possible. Therefore "strategic" aspects regarding task performance are not plausible. However, the acknowledgment of categorical membership in the distractor set provides a measure of semantic competence. This is likely to act on the featural/conceptual rather than lexico-semantic level. Therefore, recognition of the category might lead to facilitation counteracting the expected interference effect. We proposed such a mechanism to explain the attenuation of the interference effect over repeated presentation, which we found in the neurotypical cohort. If explicit processing of the category is impaired because of lesions in the semantic network, we would expect to see larger and persistent interference effects in the clinical cohort examined in this study.

For the clinical group who participated in our study, high-resolution structural MRIs were available allowing for lesion site delineation. We therefore included an exploratory analysis on lesion–symptom correlations to our investigations of the behavioral effects. Importantly, this allowed us to investigate lesion–symptom correlations for eye tracking measures such as fixations to semantic foils, that is, the dynamics of semantic processing. The evidence from participants with semantic dementia points to an involvement of the left anterior temporal lobe (ATL) in semantic competence, which is the primary atrophy site in this clinical group (Gorno-Tempini et al., 2011). The ATL has been considered a semantic hub necessary to gather and retrieve conceptual information about objects (e.g., Mesulam et al., 2009, 2013; Pobric, Jefferies, & Lambon Ralph, 2007) and can therefore be hypothesized to be involved also in categorizing semantically related distractor words.

Only few studies so far have tried to relate the semantic interference effect in patients to specific lesion patterns and have yielded inconsistent results. Using voxel-based lesion–symptom mapping (VLSM), Pino et al. (2021) were able to relate the effect to lesions in the inferior frontal gyrus. More precisely, lesions in the IFG correlated with an increased semantic interference effect in naming latencies. In addition, overall latencies in the naming task were slowed down in participants with lesions in the middle temporal gyrus (MTG), suggesting an involvement of this area in the lexical selection process. This is in line with previous findings that lesions in the MTG influence picture naming in patients with aphasia (Piai & Knight, 2018). Piai and Knight report significant semantic interference in a picture–word–interference task for patients with primary lesions in the left lateral-temporal cortex (primarily in the superior temporal gyrus [STG] and MTG). On the contrary, patients with lesions in the left pFC (middle frontal gyrus and IFG) did not exhibit an interference effect. The exact role of the left pFC and IFG, in particular, during the language production process is still elusive (see also Mirman et al., 2015; Riès, Karzmark, Navarrete, Knight, & Dronkers, 2015). Recent reviews by de Zubicaray and Piai (2019) and Nozari (2020) confirm that even taking into account neuroimaging studies, there is not yet a consensus on how exactly brain regions affording language production process are involved in the semantic interference effect. Moreover, the paradigm applied here deviates in several aspects from the classical picture–word–interference paradigm. Therefore our hypotheses concerning the VLSM analysis remain tentative. As a starting point, we assume a correlation of potential effects in naming latencies with lesions in more frontal areas in the left pFC and more temporal areas in the left lateral-temporal cortex. Based on the literature regarding semantic dementia, lesions to the left ATL can be hypothesized to correlate with eye tracking patterns reflecting impairment of overall semantic competence.

METHODS

Participants

Thirty-two participants with chronic lesions in the left-hemispheric language network, aged 17–73 years (mean = 53, SD = 11.5, 10 women), participated in this study in return for monetary compensation of €9 per hour. They were selected from a database of the Clinic for Cognitive Neurology (University Hospital Leipzig) and the Max Planck Institute for Human Cognitive and Brain Sciences. Exclusion criteria for participation were additional right-hemispheric lesions, severe overall cognitive impairment, neglect or visual field deficits, severe apraxia of speech, or reading impairments. All participants had normal or corrected-to-normal vision.

All participants were diagnosed with aphasia or residual aphasia at the time of inclusion, based on the standard German assessment battery (Aachen Aphasia Test [AAT]; Huber, Poeck, Weniger, & Willmes, 1983). Of the 32 participants, 4 participants were excluded from the final sample because of too many invalid eye tracking samples resulting from technical problems with the data sampling, or errors in voice recording. In all remaining 28 participants, structural brain imaging was available allowing for lesion delineation. Twenty-three participants had a high-resolution structural MRI acquired at the Max Planck Institute for Human Cognitive and Brain Sciences; in five participants, clinically motivated MRIs with lower slice resolution were used (for details, see Lesion–Behavior Correlations section below). The overlay of all participants is shown in Figure 1. Note that, besides the temporal lobe, the IFG is covered be the lesion overlap.

Participants underwent extensive cognitive and language-related assessments. A detailed summary of each participant's demographic and clinical information as well as their cognitive and language abilities is shown in Table 1.

Experimental procedures were approved by the institutional review board of the University of Leipzig, Germany, in accordance with the Declaration of Helsinki, and written informed consent was obtained

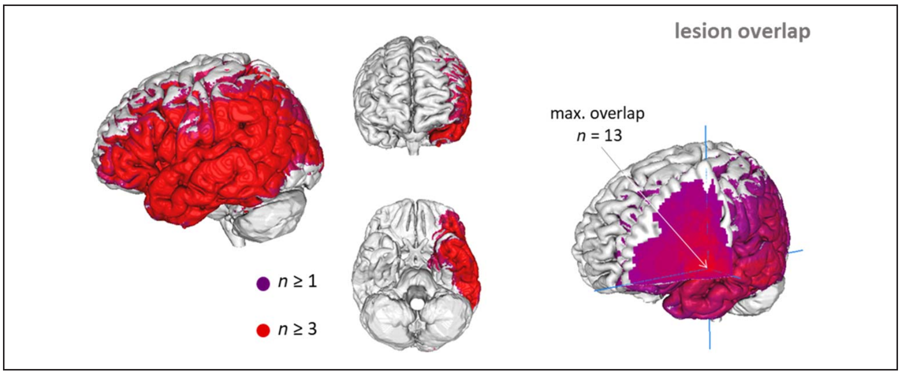

Figure 1. Overlay of all 28 patients in whom the analyses were performed. Note that the "field of view," which is a lesion overlap in three and more participants, covers the temporal lobe, the temporo-parietal junction, and the inferior frontal gyrus. Maximal overlap (n = 13) is located in the insular region, which is seen in all studies dominated by stroke lesions.

from all participants (Ethical approval to AZ 144/18-ek, Ethics Committee University Leipzig).

Materials

We used a variation of the picture–word interference approach, which is described in detail in van Scherpenberg et al. (2020). In this paradigm, instead of one, eight distractor words are presented simultaneously in each trial, in the shape of a circle, followed by the picture to be named. Out of these sets of eight words, a varying number (three, four, or five) belong to one semantic category, whereas the remaining words each stem from a different, unrelated category. The target pictures are either part of this semantic category or entirely unrelated to any of the distractor words. The material was constructed using seven semantic subcategories with six members each, resulting in a total of 42 items. See Table A1 (Appendix) for an overview of the stimuli.

Apparatus

The stimuli were presented using the Psychophysics Toolbox extension (Brainard, 1997) for MATLAB (2017a, The MathWorks) on a Lenovo Thinkpad T420 laptop (14-in. monitor, 1600 × 900 pixels resolution). The words were presented in white Arial font, size 40, on a black screen, and the pictures were scaled to 5.8 × 5.8 cm (300 × 300 pixels, 5.5° of visual angle at a distance of 60 cm between the viewer's eyes and the screen). Eye movements were recorded from both eyes using a Tobii X2-60 eye tracker with a 60-Hz sampling rate. Voice responses were recorded using a Blue Yeti USB microphone.

Design and Procedure

The variation of the number of related words in the distractor set results in a 2 × 3 design with picture Type (related vs. unrelated) and Size of lexical cohort (three, four, or five) as within-participants factors. Twelve randomized lists were created with the constraints that target pictures were separated by a minimum of two other items and that each target appeared once with a related and once with an unrelated distractor set in each block. Across each list, the participants therefore named each item 6 times. The lists were randomly assigned to the participants, by which each list was repeated a maximum of 3 times.

Each experimental session started with an instruction of the experimental procedure to which the participants consented. They were then seated in a dimly lit, soundproof room in front of the laptop and eye tracker with a distance of approximately 60 cm to the screen. A chin rest was used to minimize head movements and improve eye tracking data quality.

To familiarize the participants with the materials, each picture was presented centered on the screen with its name written underneath. In a self-paced manner, the participants named one picture after the other, and this procedure was repeated if items were not correctly named after the first familiarization (this applied only to one participant). At the start of the experimental session, the eye tracker was calibrated according to a 5-point calibration procedure, followed by three practice trials, after which any remaining questions were addressed by the experimenter.

The experimental trials were split up in three blocks with 84 trials each, in between which participants were able to take a break. Note that presentation times were increased slightly compared to the original procedure described in van Scherpenberg et al. (2020; 8 sec instead of 6 sec for the words, and 4 sec instead of 2 sec for the pictures). This accounts for additional processing costs in participants with aphasia. At the start of each trial, a fixation cross was presented in the center of the screen (0.5 sec), directly followed by the set of the eight distractor words presented in a circle around the center of the screen for 8 sec (see Figure 2 for a typical trial procedure). Participants were instructed to inspect the word set freely but were told that a minimum of three of the eight words were related to each other. During this part of the trial, participants' eye movements were recorded by a Tobii X2-60 eye tracker. Directly after the 8 sec, the distractor words disappeared, and the target picture was presented for 4 sec. Participants were instructed to name the picture as quickly and accurately as possible, and their response was recorded. After an intertrial interval of 0.5 sec, the next trial started automatically. Each trial thus lasted for 13 sec, resulting in a total experiment time of around 54 min, not including breaks.

Lesion–Behavior Correlations

For all participants entering the analysis ($n = 28$), structural imaging was available. Twenty-three scans were performed at in-house MRI scanners (3-T Siemens MRI system Trio or Verio system, Siemens Medical Systems) including 3-D T1-weighted (1-mm^3 isovoxel) and Fluid Attenuated Inversion Recovery (FLAIR) images. In five participants, MRIs from clinically motivated imaging were available, with partially lower resolution (3- to 5-mm slice thickness, including FLAIR or Turbo Inversion Recovery Magnitude and T1 images). Manual lesion delineation was performed by an experienced neurologist (H. O.) primarily based on T1 images respecting the (lower resolution) FLAIR/TIRM images. This was done using MRIcron (Rorden & Brett, 2000). All images were then transformed into standard stereotactic space (Montreal Neurological Institute [MNI]) @1 mm^3 using SPM12 (www.fil.ion.ucl.ac.uk/spm) and the *clinical* toolbox (nitrc.org/projects/clinicaltbx/). The unified segmentation approach was applied (Ashburner & Friston, 2005), and estimation of

Table 1. Demographic and Clinical Information as Well as Results from Cognitive and Language Screening for All Participants (n = 28)

Part.[a]	*Sex*[b]	*Age, years*	*m.p.o*[c]	*Syndrome*	*Etiology*	*Localization*	*Lesion size* (mm^3)	*AAT: Token Test (Errors)*[d]	*AAT: Naming (% Correct)*[e]	*RWT: Word Fluency Animals (Percentile)*[f]	*NVST (% Correct)*[g]	*LEMO: Synonyms (% Correct)*[h]	*LEMO: Reading (% Correct)*[i]
1	W	45	16	residual	SVT	temp par	199	2	NA	NA	0.97	0.90	0.97
2	M	47	55	Wernicke's	Isch	watershed post	465	23	0.88	1	0.97	0.85	0.90
3	M	51	41	amnestic	SAH/Isch	MCA/ACA	291	2	NA	NA	1.00	0.95	0.98
4	M	53	12	amnestic	metastasis	precentral	128	7	NA	NA	0.96	0.95	0.97
5	M	63	155	residual	Isch	MCA post	805	49	NA	NA	1.00	0.95	0.97
6	W	62	39	residual	Isch	MCA post	244	0	NA	NA	0.96	0.95	1.00
7	M	49	44	residual	Isch	multiple	104	3	0.93	1	0.92	0.75	0.95
8	W	60	29	amnestic	ICH	temporal	107	1	0.94	30	0.83	0.95	0.98
9	M	58	71	Broca	ICH	basal gang/insul	379	13	0.85	1	0.96	0.90	0.92
10	W	65	199	Broca	Isch	MCA temp front	1499	7	0.89	4	0.96	0.75	0.90
11	W	56	88	residual	SAH/Isch	temporal	283	0	0.89	35	0.97	0.90	0.97
12	M	48	62	amnestic	ICH	basal gang/temp	159	11	0.98	2	1.00	0.90	0.93
13	M	60	4	amnestic	Isch	MCA front	221	10	0.96	8	0.96	0.85	0.98
14	M	47	50	residual	Isch	temp par	94	5	0.97	82	0.96	0.95	0.98
15	W	57	74	amnestic	Isch	MCA front	536	11	0.92	10	0.92	0.40	0.63
16	M	56	7	residual	Isch	MCA post	260	12	0.92	10	1.00	1.00	0.85
17	W	27	72	residual	TBI/ICH/SAH	front temp	1138	4	0.99	17	0.96	0.85	0.95
18	M	41	62	residual	TBI/ICH	temp/par	128	2	1.00	45	0.96	1.00	1.00
19	W	51	46	residual	Isch	temp insul	385	0	1.00	45	0.96	0.90	0.85

Table 1. *(continued)*

Part.[a]	*Sex*[b]	*Age, years*	*m.p.o*[c]	*Syndrome*	*Etiology*	*Localization*	*Lesion size (mm³)*	*AAT: Token Test (Errors)*[d]	*AAT: Naming (% Correct)*[e]	*RWT: Word Fluency Animals (Percentile)*[f]	*NVST (% Correct)*[g]	*LEMO: Synonyms (% Correct)*[h]	*LEMO: Reading (% Correct)*[i]
20	M	51	93	Broca	SAH/Isch	front temp	2408	34	0.75	1	1.00	0.70	0.63
21	M	73	51	residual	Isch	MCA front	421	0	0.97	27	0.97	1.00	0.98
22	W	17	14	amnestic	Isch	MCA large	2638	0	0.95	1	0.88	0.60	0.82
23	M	49	8	amnestic	HSV-encephalitis	temp. basal/mesial	297	NA	0.94	17	0.96	0.95	0.98
24	M	56	65	residual	Isch/TBI	MCA front/temp	412	3	0.93	3	0.83	0.55	0.93
25	M	67	15	amnestic	Isch	basal gang/thal	233	0	0.97	7	1.00	0.95	0.93
26	W	62	126	amnestic	SAH	temp-par	1220	19	0.88	3	0.92	0.65	0.88
27	M	61	15	residual	ICH	basal gang	175	0	0.96	2	0.88	0.95	0.95
28	M	51	6	amnestic	Isch	front temp	376	0	0.94	17	1.00	1.00	0.97
Mean		**53.0**	**54.3**						**0.9**	**16.0**	**1.0**	**0.9**	**0.9**
SD		**11.5**	**46.6**						**0.1**	**20.2**	**0.0**	**0.2**	**0.1**

NA = not available.

[a] part = participant.

[b] W = woman; M = man.

[c] m.p.o = months post onset.

[d] AAT (Huber et al., 1983). The AAT is a German test battery for diagnosing types of aphasia after brain damage. The Token Test is used to diagnose the presence of an aphasic disorder by assessing language comprehension through pointing to and allocating geometrical shapes. A total number of errors of seven or less indicates no or residual aphasia. Eight to 11 indicate probable aphasia. Above 12 indicates aphasia. The reported values are the most recently available scores for each participant at the time of data collection.

[e] AAT Naming: The Naming subtest of the AAT assesses confrontation naming of 10 drawings of objects with simple nouns, 10 objects with compounds, 10 colors, and 10 actions. The maximum score is 120 (3 points per item). For the analyses, this was transformed into percentage correct.

[f] RWT (Aschenbrenner, Lange, & Tucha, 2001). In the RWT Word Fluency: Animals subtest, participants have to name as many animals as possible within 2 min. The scores are given as age-corrected percentiles.

[g] NVST (Hogrefe, Glindemann, Ziegler, & Goldenberg, in press). The NVST assesses nonverbal semantic abilities of categorizing objects according to situations and semantic features in several subtests. For the current study, a shortened version of three subtests was used. The subtests Gesture Production and Drawing were excluded. For subsequent analyses, a composite score was created from the percentage of correct responses across the three subtests.

[h] LEMO (Stadie, Cholewa, & De Bleser, 2013). The LEMO assesses different aspects of the language production system. In the Synonyms subtest reported here, participants have to find synonyms among four written words including one unrelated and one semantically related distractor word. The maximum score is 20. The score is given as percent correct.

[i] LEMO Reading: In the Reading subtest of the LEMO reported here, participants have to read aloud irregular and regular German words. The maximum score is 40. The score is given as percent correct.

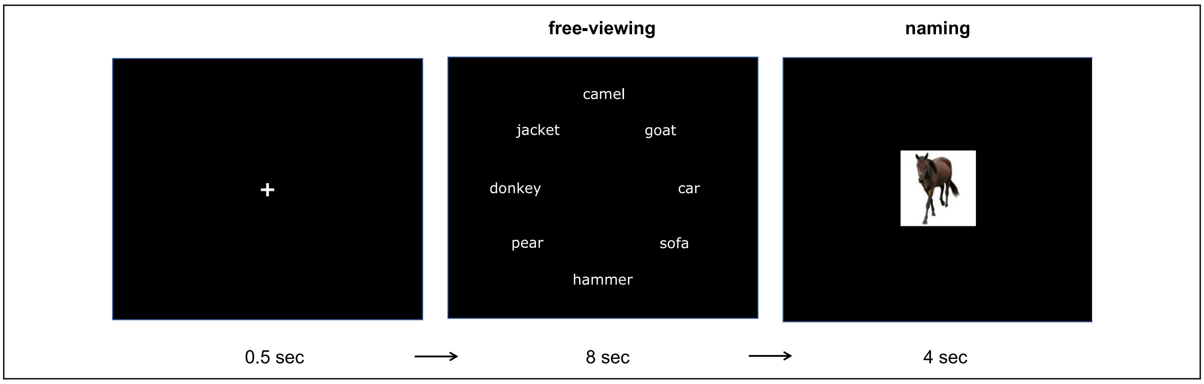

Figure 2. Exemplary procedure of a trial in which the word set contains a lexical cohort of three items from the semantic category "hoofed animals" (SET SIZE = 3). The target picture is part of the same semantic category (PICTURE TYPE = related). In the actual experiment, the words were presented in German.

normalization parameters was restricted to healthy tissue using predefined lesion masks (Brett, Leff, Rorden, & Ashburner, 2001).

Lesion–behavior correlations were performed along the principles of multivariate lesion–symptom mapping based on support–vector–regression (Zhang, Kimberg, Coslett, Schwartz, & Wang, 2014). The publicly available software used here is based on this approach (support vector regression lesion-symptom mapping [SVR-LSM] toolbox running in a MATLAB environment as published in the work of DeMarco and Turkeltaub [2018; https://github.com/dmirman-zz/SVR-LSM]). Multivariate approaches have the advantage that they take into account intervoxel correlations. Estimating lesion–symptom maps for all voxels simultaneously lesion mislocalization is attenuated while sensitivity to nonlinear relationships is enhanced (Zhang et al., 2014). The package used (SVR-LSM toolbox) provides several methods for controlling for lesion size. This is a central issue in all lesion–behavior approaches; most intuitively, it means that a behavioral difference between participants lesioned versus nonlesioned in a specific voxel is more likely to be because of a lesion elsewhere, if the overall lesion of a participant is larger.[2] Here, we chose lesion volume correction of both the behavioral scores and the lesion maps, as is recommended by DeMarco and Turkeltaub. Only voxels in which three and more participants showed lesions were included. The parameters analyzed were VOT as recorded by the voice key (VOT), fixation time as monitored by the eye tracker (FIX), and the performance in two of the clinical tests in percent correct: (i) nonverbal semantic assessment, Nonverbaler Semantiktest (NVST; Hogrefe et al., in press), and (ii) decision on visually presented synonyms with distractors, from the Lexikon modellorientiert (LEMO)-Battery (Stadie et al., 2013). Error rates were low and were not analyzed (in analogy to the linear mixed models regarding the behavioral analyses).

To infer statistical significance, the approach first assesses voxel-wise statistical significance by permutation testing. In this study, 2000 permutations were performed and only SVR-β-values with a $p < .005$ were regarded further. SVR-LSM considers all voxels simultaneously in a single model; however, to further reduce the multiple-comparison issue, a second step is based on FWE rate (with $p < .05$) for the cluster-extent threshold determined from the permutations (DeMarco & Turkeltaub, 2018).

Analysis

Picture Naming

VOTs. For the correct trials, voice onsets were determined at the start of each word, excluding stuttering, "uhms," or search behavior before a correct response. The VOTs were detected using the Chronset algorithm (Roux, Armstrong, & Carreiras, 2017) and checked manually using Praat (Boersma & Weenink, 2018). These were considered as the overt response, that is, the RTs.

Trials in which the voice recording was missing because of technical errors of the microphone (e.g., missing recordings or white noise) were discarded from all analyses (2.9%, $n = 198$ from all 28 participants).

Responses were considered incorrect and treated as errors when participants did not respond at all, responded falsely, or made false starts even when they consecutively produced a correct response (7.5%, $n = 510$). In total, 10.4% ($n = 708$) of all trials were classified as errors; these trials were excluded from the VOT analysis.

Error coding. All erroneous responses were classified according to whether they were (1) no responses, (2) semantic errors (e.g., semantic coordinates or superordinates), or (3) other errors (e.g., phonological errors, visual errors [e.g., moon → "banana"], unrelated responses).

Eye Tracking Data

From the raw data samples, fixations and saccades were detected using the GazePath algorithm (van Renswoude et al., 2018) on the mean x- and y-coordinates of the left and right eye. Areas of interest were defined as rectangles of 270 × 170 pixels around each word in the circular word set. To correct fixations that were distorted because of head movements, we calculated the minimum euclidean distance between each data point in the fixation data frame and the eight areas of interests. This value was then used to adjust the drift of each distorted data point toward the position of the respective word in the word set.

Observations where GazePath failed to detect any fixations were excluded from the analysis (n = 3344, 5.9%). Combining data loss from VOT and eye tracking data, around 15% were not available for the consecutive statistical data analysis.

Statistical Analysis

All statistical analyses were performed using R version 3.6.1 (R Core Team, 2016). Linear mixed effect models were run with random slopes for subjects and items, using the *lme4* package in R for linear mixed models (Version 1.1-21; Bates, Mächler, Bolker, & Walker, 2015), and p values were determined using the package *lmerTest* (Kuznetsova, Brockhoff, & Christensen, 2017). All code and anonymized data can be downloaded here: osf.io/ezcgk/.

RESULTS

VOTs and Naming Errors

The mean VOT for the group across naming conditions is provided in Table 2 and illustrated in Figure 3. Overall, naming of semantically related pictures was 34 msec slower compared to naming of unrelated pictures, and descriptively, this interference effect was strongest for the condition with four distractor words (42 msec). On average, participants made 11 errors for related pictures and 10 errors for unrelated pictures. Given 126 trials per picture type condition, these error rates are quite low (around 8% of all trials). Considering that, across set sizes the error rates were even lower, and that, descriptively, the differences between conditions were minor, we did not analyze errors further statistically.

The effects were confirmed in a generalized linear mixed model (GLMM) with a fully specified random structure (main effects and interaction term for picture TYPE and set SIZE for both subjects and stimuli) without correlation parameters. Sliding difference contrasts were used to code the pairwise comparisons of picture type (related vs. unrelated) and set size (five vs. three and four vs. three distractor words) directly within the model.

The analysis revealed a significant main effect of picture type, indicating that related pictures were named significantly slower than unrelated pictures (estimate = 34.71, SE = 15.08, t = 2.3, p = .021). The main effect of set size was nonsignificant (four vs. three distractor words: estimate = −4.96, SE = 13.61, t = −0.36, p = .715; five vs. three distractor words: estimate = −6.16, SE = 15.8, t = −0.39, p = .697). Importantly, the interactions between picture type and set sizes were nonsignificant as well (for four vs. three and five vs. three distractor words both ts < 0.54, p > .587). This was confirmed by a nested model, where the effects of picture type were nested under the levels of set size. The results reveal a statistically significant interference effect at all set sizes (three distractor words: estimate = 36.25, SE = 5.2, t = 6.97, p < .001; four distractor words: estimate = 37.86, SE = 7.28, t = 5.2, p < .001; five distractor words: estimate = 28.88, SE = 6.54, t = 4.42, p < .001). This means that, contrary to our predictions, additional distractor words did not significantly affect naming latencies. These results are summarized in Figure 3. For comparison, we provide results by neurotypical participants (n = 24) described in van Scherpenberg et al. (2020) in the same plot.

When comparing the current clinical cohort to the previously reported neurotypical cohort of young participants, age and age range differ dramatically. To address an age group effect formally, we are currently investigating younger (18–32 years) and older (60–70 years) participants with the paradigm (paper in preparation). To assess the additional aspect of age range, we performed the current and following analyses including age as a covariate in the GLMM. This yielded the qualitatively same results (see Appendix Table B1).

Establishing this novel paradigm in young, neurotypical participants, we found an item repetition effect.

Table 2. Mean VOTs in Milliseconds and *SEM*s for Each Naming Condition

Distractor Set Size	*3*		*4*		*5*		*Total*	
Picture type	related	unrelated	related	unrelated	related	unrelated	related	unrelated
Mean VOTs in ms	1333.08	1302.23	1335.94	1293.94	1326.52	1297.11	1331.86	1297.75
SE	16.07	15.25	15.65	14.78	16.19	15.24	11.90	11.25
Interference	30.85		42.00		29.41		34.11	
Mean no. of errors	4.74	5.06	3.86	3.86	4.40	4.05	10.96	10.32

Values are adjusted for within-participant designs following Morey (2008).

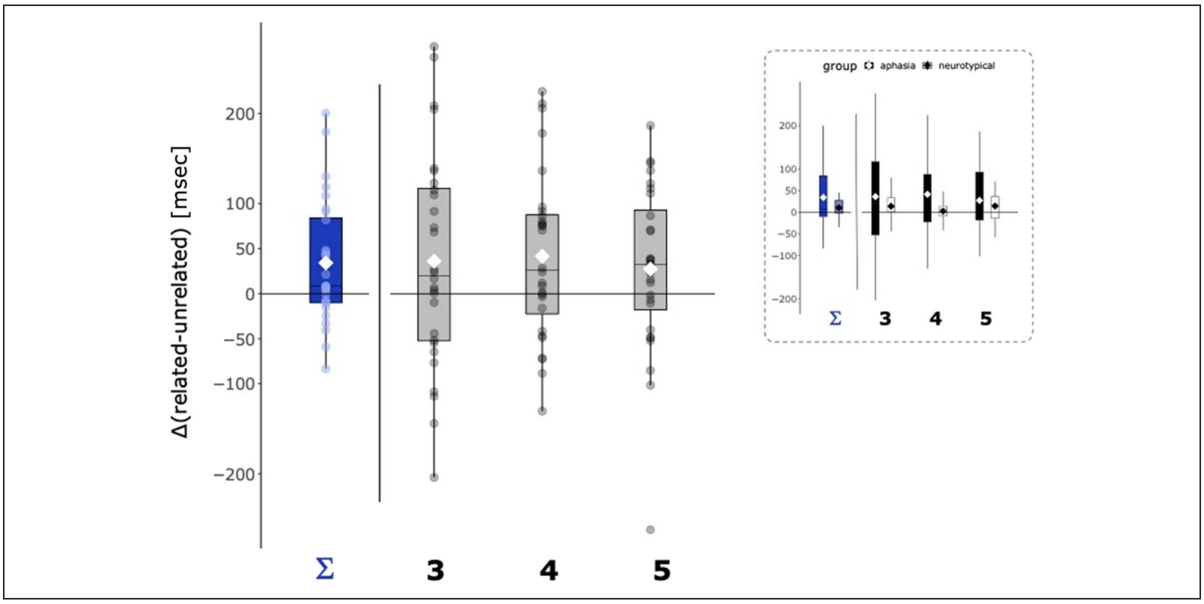

Figure 3. Interference effect in total and across number of distractor words for participants with aphasia. Boxplots show mean, median, upper and lower quartiles, and range. Dots represent individual means. For numerical values, see Table 2. The inset shows a comparison of the effect between the participants with aphasia (darker shades) and neurotypical participants (lighter shades, n = 24; see van Scherpenberg et al., 2020, for details).

Item repetition had an effect on naming latencies and the semantic interference effect, reducing both significantly across repetitions. We therefore ran another model for the clinical population in the current study, including repetition as a covariate (mean-centered and standardized) in interaction with picture type. The fully specified random structure was supported and reached convergence. This analysis revealed main effects of picture type (estimate = 39.75, *SE* = 15.19, t = 2.62, p = .009) and repetition (estimate = −65.68, *SE* = 9.94, t = −6.61, p < .001). In contrast to the neurotypical population, however, results in the clinical population show no interaction between picture repetition and picture type (estimate = 8.02, *SE* = 15.17, t = 0.53, p = .597). This indicates that, although naming latencies decreased linearly by ~66 msec, on average, across repetitions, the semantic interference effect remained stable in the clinical population as illustrated in Figure 4, again including the comparson to the neurotypical population. The results remained the same when including age as a covariate in the model (Appendix Table B2).

Fixation Durations

Prior to the naming task, participants viewed the distractor words arranged in a circle and fixations on these words were analyzed separately. Note that, in each trial, three, four, or five words were members of a semantic category whereas the remaining (five, four, or three, respectively) were nonmembers. To evaluate statistically the difference in fixation durations between the category members versus nonmembers, we ran a generalized linear mixed model with fixation durations as the dependent variable and word type (member vs. nonmember) and set size (three, four, or five) as fixed effects. All fixed effects were coded with sliding difference contrasts. Again, we accounted for by-subject and by-stimulus random slopes, and the final converging model included a fully specified random structure, without correlation parameters and one contrast of the factor set size. None of the contrasts were significant, indicating no significant difference between fixation durations on category members versus nonmembers, independent of the number of categorically related words (all *t*s < 0.874, all *p*s > .382; see Figure 5 and Figure C1 [Appendix] for details). As described in the work of van Scherpenberg et al. (2020) and illustrated in Figure 5, this finding is clearly different from the pattern we observed with neurotypical participants, who fixated longer on category members independent of set size. Including age as a covariate, we observe that this main difference in fixation duration remains nonsignificant (see Appendix Table C1).

Subsequently, we investigated whether fixation durations on category members had an effect on naming latencies, in interaction with picture type. We therefore added fixation durations as a covariate (mean-centered and scaled) to a generalized linear mixed model, with VOT as dependent variable and picture type as fixed effect. The model with a fully specified random structure without correlation parameters converged.

The analysis revealed no influence of fixation durations on naming latencies (estimate = 2.88, *SE* = 10.33, t = 0.28, p = .781) and no interaction with picture type (estimate = 10.04, *SE* = 15.81, t = 0.64, p = .525). The main

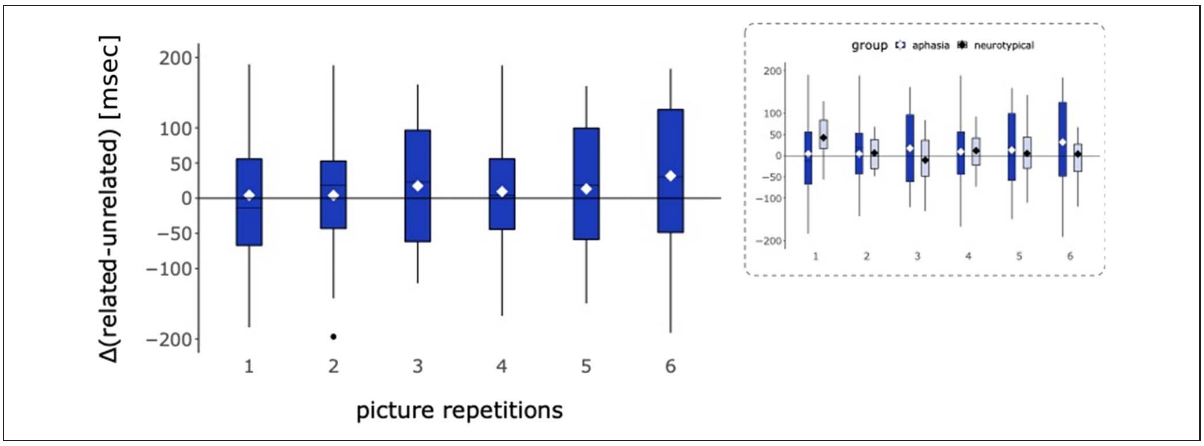

Figure 4. Interference effect across picture repetitions for participants with aphasia. Boxplots show mean, median, upper and lower quartiles, and range. The inset shows a comparison of the effect between the participants with aphasia (darker shades) and neurotypical participants (lighter shades, $n = 24$; see van Scherpenberg et al., 2020, for details).

effect of picture type remained significant (estimate = 31.27, $SE = 15.47$, $t = 2.02$, $p = .043$).

Correlations with Clinical Linguistic Measures

Finally, we correlated a selection of the clinical linguistic measures with our experimental effects. The linguistic measures (see Table 1) included reading abilities (LEMO Reading), synonym judgments (LEMO Synonyms), general naming abilities (AAT Naming), semantic word fluency (Regensburger Wortflüssigkeits-Test [RWT]: Animals), and nonverbal semantic abilities (NVST). We were particularly interested in how these measures might be related to the semantic interference effect, or the difference in fixation durations between category members and nonmembers. These individual effect sizes were taken from the estimated Subject coefficients of the linear mixed models described above to account for interindividual or item-based variation. The semantic interference effect did not correlate with any of the test scores. However, performance in the NVST correlated with the differences in fixation durations to category members versus

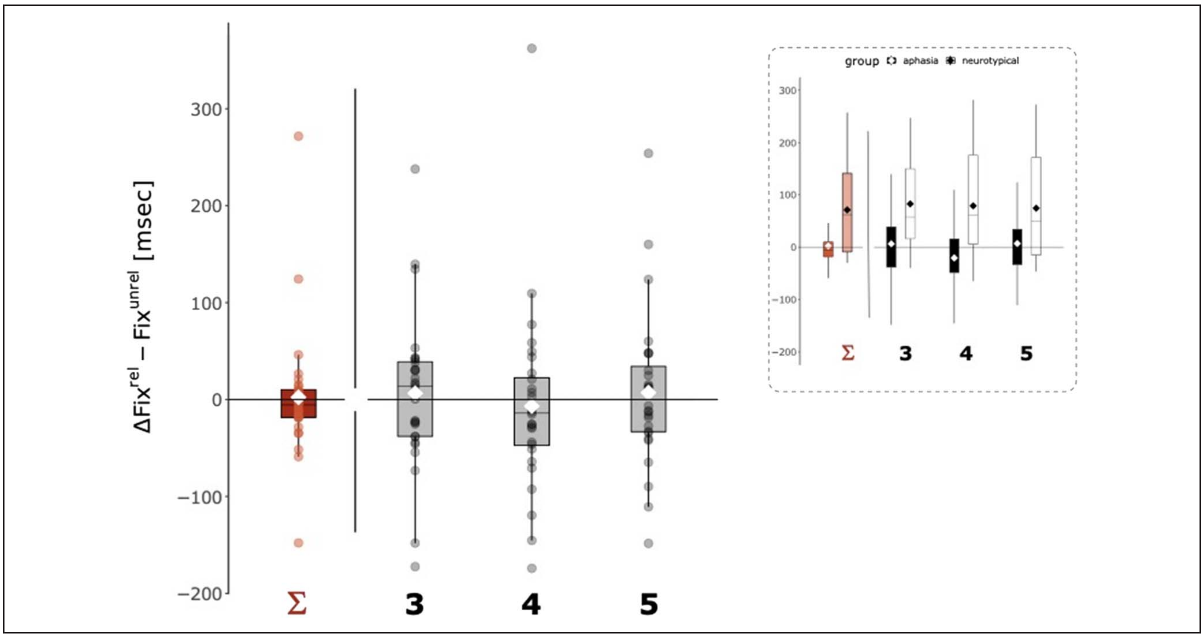

Figure 5. Fixation durations for each word as part of the distractor word set for participants with aphasia. Boxplots show mean, median, upper and lower quartiles, and range. Dots represent individual means. The inset shows a comparison of the effect between the participants with aphasia (darker shades) and neurotypical participants (lighter shades, $n = 24$; see van Scherpenberg et al., 2020, for details).

nonmembers (rho = .463, p = .013): The better participants scored in the NVST, the more they preferentially fixated on categorically related words, indicating acknowledgment of the semantic category. The (Spearman rank) correlations are summarized in Table D1 (Appendix).

Lesion–Behavior Correlations

In our exploratory lesion–behavior analysis, we used mean individual VOTs and fixation times (FIX) during the exploration of the eight distractor words. For both parameters, we analyzed the respective value for the related and the unrelated conditions and their difference. Moreover, we correlated individual lesions with individual scores in the clinical tests.

For VOT, the behavioral score was the mean response time after picture onset with $\text{VOT}^{\textbf{rel}}$ if the picture belonged to the same category as the semantic category in the distractor word set, and $\text{VOT}^{\textbf{unr}}$ for pictures unrelated to the category. For the analyses, the respective other parameter was entered as a covariate in the SVR-LSM model (i.e., $\text{VOT}^{\textbf{rel}}$ as a covariate for the analysis of $\text{VOT}^{\textbf{unr}}$ and vice versa). An additional analysis was performed with the mean difference between related and unrelated conditions ($\Delta(\text{VOT}^{\textbf{rel}} - \text{VOT}^{\textbf{unr}})$). In this case, $\text{VOT}^{\textbf{mean}}$ was introduced as a covariate in the SVR-LSM. For fixation time, the same values were calculated (i.e., $\text{FIX}^{\textbf{rel}}$, $\text{FIX}^{\textbf{unr}}$, and $\Delta(\text{FIX}^{\textbf{rel}}\text{-FIX}^{\textbf{unr}})$). Regarding the interpretation of the results, it is relevant to consider the assumptions of the SVR-LSM model. Although for overall VOT it is intuitive that larger values are expected as a sequel of a lesion in a relevant brain area, the strength of interference effect may result in a seemingly paradoxical behavior. That means that a lesion may attenuate the interference effect, thereby resulting in relatively shorter VOT compared to a participant without a lesion. Therefore, results listed in Table 3 and illustrated in Figure 6 and Figure 7 regard lesion sites that correlate with

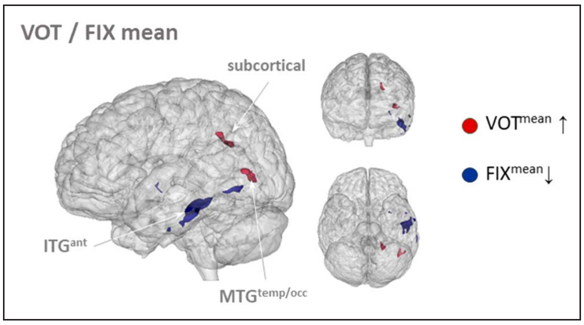

Figure 6. Clusters (uncorrected) corresponding to shorter fixation during the presentation of the distractor words ($\text{FIX}^{\textbf{mean}}$↓, blue) and longer naming latencies ($\text{VOT}^{\textbf{mean}}$↑, red). Specifications of the clusters are provided in Table 3.

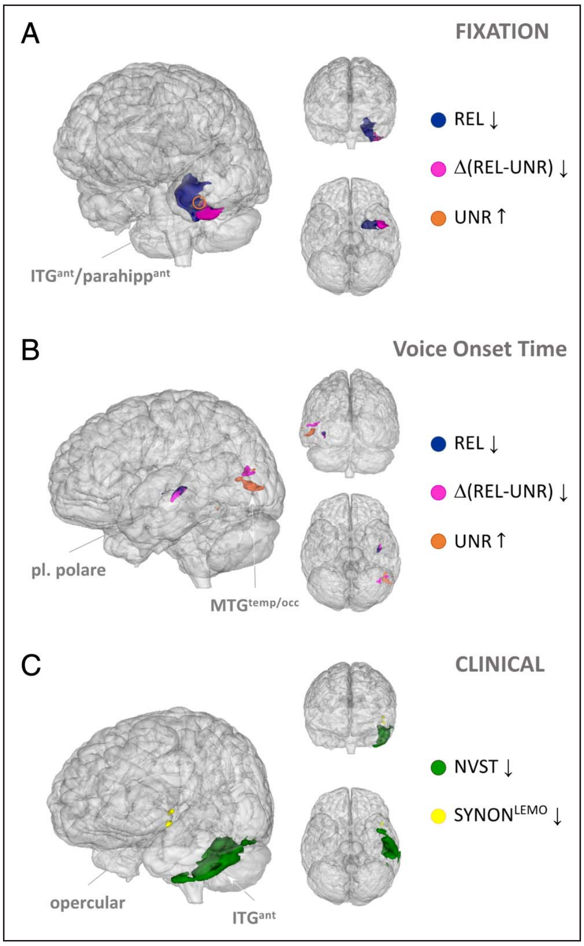

Figure 7. Clusters (uncorrected) corresponding to the behavioral effects of VOT ($\text{VOT}^{\textbf{rel}}$, $\text{VOT}^{\textbf{unr}}$, $\Delta\text{VOT}^{\textbf{rel-unrel}}$) and FIX ($\text{FIX}^{\textbf{rel}}$, $\text{FIX}^{\textbf{unr}}$, $\Delta\text{FIX}^{\textbf{rel-unr}}$) as well as the clinical measures assessing semantic abilities (NVST and $\text{SYNON}^{\text{LEMO}}$). Specifications of the clusters are provided in Table 3.

a deviation from the expected behavior (which has been documented in the neurotypical young control group). The clusters listed and illustrated did not survive the more conservative cluster-based correction for multiple comparisons. Therefore, results must be interpreted with caution.

As illustrated in Figure 6, lesions in a cluster in the anterior inferior temporal gyrus (ITG) reduced mean fixation time during the presentation of the distractor words, whereas a cluster in the posterior portion of the MTG increased VOT signaling slower naming. The second cluster corresponding to VOT increases is located in the subcortical white matter.

Regarding the question in how far lesions in specific areas may modulate the categorical analysis during the presentation of distractor words (FIX), Figure 7A illustrates that lesions in a large cluster in the ATL correspond to a decrease in relative fixation of the related words. This

Table 3. Results of the SVR-LSM

	Size mm^3	Dia mm	p^{max}	MNI of Peak x	y	z	Harvard	aal	Brod
VOT									
mean ↑	273	4.0	*.001*	−45	−55	0	$MTG^{temp\text{-}occ}$	MTG	37
	243	3.9	*.002*	−27	−51	26	*n.d.*	*n.d.*	*n.d.*
Δ (rel-unr)↓	218	3.7	*.001*	−47	−55	3	$MTG^{temp\text{-}occ}$	MTG	37
	133	3.2	*.001*	−41	−6	−12	pl. polare	STG	*n.d.*
rel ↓	222	3.8	< *.001*	−41	−6	−12	pl. polare	STG	*n.d.*
unr ↑	407	4.6	*.002*	−47	−54	−1	$MTG^{temp\text{-}occ}$	MTG	37
FIX									
mean↓	957	6.1	*.001*	−48	1	−41	ITG^{ant}	ITG	20
	301	4.2	*.001*	−67	−40	−20	ITG^{ant}	ITG	20
Δ(rel-unr)↓	620	5.3	*.001*	−43	−1	−43	ITG^{ant}	ITG	20
rel ↓	2316	8.2	*.002*	−34	3	−42	temp pole	temp $pole^{mid}$	36
unr ↑	81	2.7	*.004*	−34	3	−42	temp pole	temp $pole^{mid}$	36
CLINICAL									
NVST % ↓	4643	10.3	< *.001*	−46	−9	−46	ITG^{ant}	ITG	20
SYN % ↓	103	2.9	< *.001*	−48	17	−13	temp pole	temp $pole^{sup}$	38

The largest clusters for the respective parameters are listed. Note that, in the clusters, each voxel passed the $p < .005$ threshold, whereas none of the clusters survived more conservative cluster-based correction. The table provides the cluster size in mm^3 and as the diameter of a sphere corresponding to the volume (Dia). p^{max} denotes the maximal statistical threshold reached in the cluster. MNI coordinates and regions according to three different atlases are provided (Harvard-Oxford atlas, Automated anatomical labeling atlas, Brodman atlas; n.d. indicates not defined in the atlas). The direction of the arrow in the first column indicates the direction in which a lesion would modulate the parameter, that is, ↓: lesion will decrease the numerical value and ↑: lesion will increase the numerical value.

cluster is closely collocated to a cluster in which lesions correspond to a decrease in the difference between relative fixation of related minus fixation of the unrelated distractor words ($\Delta FIX^{\textbf{rel-unrel}}$↓). A much smaller cluster in which lesions correspond to increasing relative fixation on unrelated words ($FIX^{\textbf{unrel}}$↑) largely overlaps with parts of the two above clusters. The fact that lesser fixation on related words ($FIX^{\textbf{rel}}$↓) is the more prominent cluster confirms the intuitive prediction that difficulties to recognize the categorical relationship should mostly decrease preferential fixation of related words. This finding is complemented by a correlation of a large cluster in the ATL (anterior part of the ITG) with a decrease in the performance in the NVST test, assessing nonverbal semantic abilities (Figure 7C).

Regarding the interference effect on naming, the results suggest that lesions in a cluster of the posterior MTG and another cluster in the STG/planum polare correlate to smaller interference ($\Delta VOT^{\textbf{rel-unrel}}$↓; Figure 7B). While the posterior cluster (MTG) is close to a cluster in which VOT for unrelated pictures increases ($VOT^{\textbf{unrel}}$↑), the cluster in the mid STG partially overlaps with a decrease in VOT for related items ($VOT^{\textbf{rel}}$↓).

DISCUSSION

Lesions to the left-hemispheric language network regularly interfere with the ability of prompt and correct retrieval of words. Clinically, this results in the slowing of speech production and erroneous choice of lexical entries. One common type of such errors is semantic paraphasias leading to the substitution of a target word by a semantically related word (Schwartz, 2014). Although it is the clinical goal of speech and language therapy to restore fast and precise lexical retrieval in PWA, error patterns in these speakers may shed light on how our brain supports the remarkable ability of seemingly effortless language production. This, in turn, may allow for developing theoretically grounded therapy schemes also for confrontational naming training, a cornerstone of speech and language therapy in aphasia (Off, Griffin, Spencer, & Rogers, 2016; Lorenz & Ziegler, 2009).

In this vein, we here investigate participants with a chronic lesion to the left-hemispheric language network, all of whom showed overt aphasia in the acute stage of their disease and suffered from mild to moderate or residual aphasia at the time of testing. To inquire in how an acquired lesion impacts on lexico-semantic processing, we used a novel semantic interference paradigm as previously investigated in neurotypical young participants (van Scherpenberg et al., 2020). Our results contribute to the question of how semantic context, generated by a set of eight distractor words, affects language production after brain lesions causing aphasic deficits. We used a combined eye tracking and picture naming paradigm, to help provide evidence for two aspects of lexical retrieval: (i) the dynamics of analysis of a set of words regarding their semantic relation and (ii) efficiency and modulation of picture naming in a controlled semantic context. Besides implications for models of language production, the study adds to the growing body of work demonstrating feasibility and fruitfulness of complex language production paradigms in heterogeneous cohorts of people with residual to moderate language impairment.

At the group level, participants showed a strong semantic interference effect elicited by categorically related distractor words. The effect is significantly larger than that in neurotypical speakers. Notably, it is not correlated to clinically applied, linguistic tests including those targeting word-level deficits. In line with findings in the neurotypical cohort, the interference effect is independent of the number of distractor words (i.e., no difference between three, four, and five categorically related distractor words). Also in line with the findings in the neurotypical group, duration of fixation on the semantically related distractor words did not predict naming latency. Although overall naming latencies decreased significantly over the course of the experiment, the interference effect was stable across repetitions of the same picture across all trials. This contrasts findings in the neurotypical group, who showed interference only in the first cycle of naming. Interestingly, eye tracking additionally revealed that participants fixated equally long on all words. Thereby, the preferential fixation of categorically related words in the neurotypical cohort is not preserved in the group of participants with a lesion to the language network. It is noteworthy, however, that participants who showed a preferential fixation on categorically related words performed better in the clinical test assessing overall semantic abilities (NVST). It should be noted that the reported results remained the same when including age as a covariate in the statistical models, showing that the age range of our participants did not influence the group behavior. Instead, the effects are more likely related to the specific changes because of the aphasic deficit and the underling lesion in the language network.

The above behavioral results are complemented by findings of explorative lesion–behavior correlational analyses. Regarding overall semantic abilities, lesions in the ATL correlated with lesser performance in overall semantic (NVST↓) and synonym judgment ($\text{SYNON}^{\text{LEMO}}$↓) abilities. The fact that lesions in similar clusters in the ATL correlate with smaller fixation preference for related compared to unrelated words ($\Delta\text{FIX}^{\text{rel-unrel}}$↓) suggests a common underlying neuronal network. With regard to the semantic interference effect on lexical retrieval, lesions in the posterior MTG and in the STG/planum polare correlate with a smaller interference effects (as evidenced be VOTs: $\Delta\text{VOT}^{\text{rel-unrel}}$↓).

We will first briefly discuss two findings that are in line with the findings in the neurotypical population previously reported (van Scherpenberg et al., 2020). We then discuss the focus of this paper, that is, in how far a brain lesion elicits changes in semantic categorization and overt picture naming, while taking into account the results of our exploratory lesion behavior correlations.

Naming Latencies Are Independent of the Number of Categorically Related Distractors and the Categorical Fixation Preference

Findings in the clinical and neurotypical group converge in that semantic interference is not affected by set size. For the clinical group, a significant effect is observed at three, four, and five categorically related distractor words (~36, ~38, and ~29 msec, respectively); that is, the effect did not increase with additional distractors. This supports the assumption that reading of more categorically related distractor words does not induce more competition on target word retrieval. Besides number of overtly presented categorical distractors, longer fixation on semantically related distractor words did not increase interference in both PWA and neurotypical groups. This provides confirmatory evidence for the notion that once a threshold is reached, autochthonous, implicit activation of the lexical cohort is triggered leading to competition (Piai, Roelofs, & Schriefers, 2012). The lack of effects of number of categorical distractor words and fixation duration shows that cohort activation does not depend on these two parameters. Lexical competition must be considered a function of pre-established parameters of the specific category, such as size of and semantic proximity within the cohort (Rose, Aristei, Melinger, & Abdel Rahman, 2019; Rabovsky, Schad, & Abdel Rahman, 2016; Aristei & Abdel Rahman, 2013; Vigliocco, Vinson, Damian, & Levelt, 2002).

PWA Show Large Semantic Interference, Stable across Naming Repetitions

The semantic interference effect observed in PWA is numerically much stronger than that of neurotypical participants (~30 vs. ~10 msec). Moreover, contrary to the neurotypical group, the effect in the clinical population is stable across naming repetitions of the same item. Despite an overall decrease in naming latency across repetitions (~66 msec, on average), the interference effect remained stable (no interaction of picture type and repetition). In the neurotypical group, both overall VOT and the interference effect ($\Delta VOT^{rel-unrel}$) decreased significantly. This suggests that the lesioned network shows larger vulnerability of the correct lexical retrieval and cannot afford substantial learning of the interference suppression. Alternatively, increasing facilitatory effects within the lexico-semantic network may explain the attenuation of the interference effect as documented in our previously examined neurotypical cohort. The progressive familiarization with the limited number of seven categories would strengthen featural/conceptual aspects of the category. There is converging evidence that, at the conceptual level, facilitation is elicited by semantic membership. Therefore, the larger and persistent interference effect in the present cohort of people with a lesion in the lexico-semantic network may point to a deficit at this level of the naming process. We will come back to this aspect below.

Previous evidence on semantic interference in PWA based on the picture–word–interference task is inconclusive. Some studies demonstrated a robust effect at the group level (Pino et al., 2021; Piai & Knight, 2018; Hashimoto & Thompson, 2010), whereas others failed to report a significant effect in cohorts or in single-case studies (Piai, Riès, & Swick, 2016; Wilshire et al., 2007). Our study adds evidence of the effect in participants with aphasia over and above specific lexico-semantic abilities. The lack of significant correlations to clinical assessments on naming, word fluency, or semantic abilities suggests that standard patholinguistic diagnostics are largely "blind" to interference by categorical distractors. This may be of note for clinical perspectives because categorical distractor-induced interference is qualitatively similar but substantially larger when compared to neurotypical participants.

The explorative VLSM analyses showed lesions in the left lateral-temporal cortex (STG and MTG) to decrease the interference effect. It highlights the region's key role in picture naming, more specifically the suggestion that temporal areas are essential for activation of the lexical target (Baldo, Arévalo, Patterson, & Dronkers, 2013). A decrease in inference may seem counterintuitive at first; however, co-activation of a lexical cohort can be assumed to be likewise affected by the lesion (Harvey & Schnur, 2015; Henseler, Mädebach, Kotz, & Jescheniak, 2014). Interestingly, results of a brain stimulation study in neurotypical participants (Pisoni et al., 2012) have been interpreted in exactly this vein: Less efficient activation of lexical entries reduces the number of co-activated lexical competitors, thereby reducing the inhibitory effect on target retrieval. Our exploratory lesion analysis supports this notion.

Semantic Interference Does Not Depend on Explicit Acknowledgment of Semantic Category

Neurotypical participants fixated longer on categorically related when compared to unrelated words in the distractor word set. As discussed above, there was no explicit instruction to do so, nor can the preferential fixation on cohort members be considered strategical for the task, which required to name a picture, not contained in the distractor set. The finding in neurotypical participants indicates an acknowledgment or explicit processing of the semantic category present in the word set. Interestingly, this categorization effect was not found in the current study. Participants with aphasia showed no fixation preference for categorically related words. The finding is particularly relevant in that it speaks for a non-straightforward relationship between categorical semantic processing and lexical retrieval. This requires discussion.

Apart from the picture–word–interference task, blocked cyclic naming and continuous naming paradigms elicit semantic interference and may shed light on the relationship between semantic and lexical processing. In the blocked cyclic naming paradigm, pictures are named consecutively either within homogenous blocks of one semantic category, or heterogeneous blocks of several semantic categories (Crowther & Martin, 2014; Belke & Stielow, 2013; Schnur, Schwartz, Brecher, & Hodgson, 2006; Belke, Meyer, & Damian, 2005). Here, semantic interference reliably appears in the comparison of naming latencies between the two naming settings: Pictures are named more slowly in homogenous than in heterogeneous blocks. By repeated retrieval of members of the same semantic category, their lexical representations form a strong cohort of mutual competitors, constantly inhibiting retrieval of the respective target lexical representation. Recently, it has been debated that the blocked cyclic naming paradigm leaves room for additional, task-related strategies potentially influencing the effect: Because of the repetitively presented semantic categories, neurotypical participants become familiar with the items in the set, which may allow them to bias the lexical-semantic representations of the set members, increasing efficiency of lexical retrieval (Belke, 2017a, 2017b). This suggests that, in the blocked cyclic paradigm, participants are aware of the semantic relationship of the pictures they are naming. Although this effect does not override the inhibition of naming latencies within blocks, it counteracts accumulation of interference across blocks. The assumption is supported by the fact that participants with lesions in the left pFC do exhibit stronger cumulative effects, that is, stronger semantic interference also across blocks (Riès et al., 2015; Belke & Stielow, 2013; Schnur et al., 2009). Lesions in this area, known to be involved in executive control functions and retrieval of semantic knowledge (Thompson-Schill, Bedny, & Goldberg, 2005; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997), may compromise the top–down bias of the lexical-semantic representations of the set members in the respective cycle.

On the contrary, in the continuous naming paradigm (Schnur, 2014; Oppenheim, Dell, & Schwartz, 2010;

Howard et al., 2006), pictures are also named consecutively, but in seemingly random order with category members separated by pictures from other categories as well as fillers. Nevertheless, with each new member of a category that has to be named, latencies have been shown to cumulatively increase (see also Kuhlen & Abdel Rahman, 2017; Rose & Abdel Rahman, 2017). Even though participants are likely not aware of the categorical relationship of the pictures because of their seemingly random distribution, their relatedness nevertheless exerts an inhibitory function on naming latencies. The continuous naming paradigm therefore supports the understanding that explicit processing of a semantic relationship is not necessary to induce interference.

The current study adds to this debate. On the one hand, our study demonstrates robust and large semantic picture–word interference induced by multiple semantic distractors, in a group of participants with chronic lesions in the left-hemispheric language network including the temporal lobe and IFG. However, this effect is not dependent on explicit processing of the semantic category, which participants viewed as part of the circular word set beforehand. Participants fixated equally long on semantically related compared to unrelated words. This pattern is clearly different from our findings in neurotypical participants (van Scherpenberg et al., 2020) but resembles findings in participants with semantic memory impairment. As reported by Seckin et al. (2016) and Faria et al. (2018), individuals with semantic dementia spent more time fixating on unrelated picture foils in a visual world paradigm, compared to neurotypical participants. Participants in this study did not exhibit strong difficulties in semantic processing, as indicated by the clinical tests (LEMO Synonyms; NVST nonverbal semantics tasks; see Table 1). However, correlations between the experimental measures and the test scores revealed that the better participants performed in the NVST, the bigger the difference in fixation durations between category members and nonmembers, indicating a higher ability for semantic differentiation. In addition, the explorative lesion–symptom correlations showed that both lower performance in the NVST and LEMO Synonyms task as well as a decreased difference in fixation durations correlated with lesions in the ATL. The ATL has been described to have the function of a semantic hub integrating multimodal semantic information (e.g., Mesulam et al., 2009, 2013; Pobric et al., 2007). Although interpretation of our VLSM analyses is tentative, results point to an involvement of the ATL in our modified picture–word interference paradigm. We suggest that lexical information from the written words is mapped on their (amodal) semantic correspondence, which would be the prerequisite to explicitly acknowledge their semantic categorical relationship. Lesions in the ATL may compromise this ability, whereas lexical co-activation, as a prerequisite for the interference effect, is largely preserved.

Despite the absence of explicit semantic categorization, naming latencies were significantly delayed when the target picture was categorically related to the distractor word set. Moreover, the effect was even stronger than that in the neurotypical population, who showed a clear semantic categorization effect as evidenced by fixation durations. These findings confirm the assumption that semantic information from lexically activated distractors (be it written distractor words or previously named pictures) is implicitly processed to activate further category members. Although somewhat speculative, the absence of a relationship between frontal (IFG) lesions and either aspect of the experimental task performance may point in the same direction. The implicitly activated category members, in turn, form a cohort of lexical competitors, which inhibit target selection when the target is part of the same semantic category (lexical competition hypothesis, e.g., Abdel Rahman & Melinger, 2009, 2019; Melinger & Abdel Rahman, 2013; La Heij et al., 2006; Wheeldon & Monsell, 1994).

It should be noted that, in our paradigm, the SOA, that is, the time between first presentation of a distractor word and display of the target picture (8 sec), was substantially longer than that in typical picture–word–interference tasks. We used the long SOA to ensure that each word was processed. On average, participants fixated ~720 msec on each word in the word set. Therefore, even if lexico-semantic processing was slowed in our clinical population, the exploration time of 8 sec can be assumed sufficient to retrieve the semantic content of the words and activation of a cohort of competitors. In fact, the single-case study by Wilshire et al. (2007) revealed (a trend toward) semantic interference only after enough time had passed for successful semantic activation of the distractor word (at SOA of +200 or +400 msec). We therefore suggest that the paradigm described here adds further evidence that semantic interference through lexical competition is independent of explicit processing or acknowledgment of semantic information of previously activated distractors of pictures. However, the fact that we do find interference for related compared to unrelated distractor words implies that implicit, automated semantic processing must have taken place for the distractor words to function as competitors inhibiting naming.

Conclusion

Taken together, the results of the current study add to the knowledge on semantic context effects during word retrieval in aphasia. We applied a complex novel multi-word picture–word–interference paradigm combining both naming latency as well as eye movement measures, to examine the relationship between explicit processing of the semantic content of the distractor words and their inhibitory effect on the following naming task. We replicated a robust semantic interference effect from multiple simultaneously presented distractor words, which was substantially larger than that of a neurotypical population in the same paradigm. Comparable to the results from the neurotypical population, the size of the effect did not depend on the number of distractors in the word set and was not modulated by longer fixation durations to the semantically related distractor words. This is in line with the concept that, if activation of a semantic category passes a threshold, the activation of the lexical cohort is implicit and automatic and cannot be augmented by overtly adding members to the lexical cohort or longer processing of the lexical entries does not further modulate lexical competition during the word retrieval process. In the same vein, the interference effect arose despite no explicit processing of the categorical relationship between the distractor words. The participants with a lesion in the lexico-semantic network fixated equally long on members and nonmembers of the semantic category present in the word set. This supports the assumption that implicit, automatic semantic activation upon reading the distractor words is sufficient to cause interference.

Notably, a smaller difference in fixations on category members versus nonmembers correlated with lower nonverbal semantic abilities (in the NVST task) and lesions in the ATL, confirming an involvement of this amodal semantic hub in explicit semantic processing in this task. Because conceptual-level semantics are generally agreed on to facilitate naming, impairment at this level may explain why our clinical cohort showed a larger and persistent interference effect, when compared to the previously tested neurotypical cohort. Future research could corroborate this implication by assessing the relationship of semantic processing and naming abilities in participants with semantic dementia, whose semantic competence is known to be strongly impaired, because of atrophy in the ATL.

APPENDIX A: STIMULI

Table A1. List of Stimuli

Category	*Items*					
hoofed animals	Reh (deer)	Pferd (horse)	Esel (donkey)	Schaf (sheep)	Kamel (camel)	Ziege (goat)
fruits	Apfel (apple)	Birne (pear)	Traube (grape)	Erdbeere (strawberry)	Kirsche (cherry)	Orange (orange)
seating furniture	Sofa (couch)	Stuhl (chair)	Hocker (stool)	Sessel (armchair)	Bank (bench)	Thron (throne)
carpenter's tools	Hammer (hammer)	Säge (saw)	Schraube (screw)	Axt (axe)	Zange (pliers)	Bohrer (drill)
face parts	Auge (eye)	Nase (nose)	Mund (mouth)	Ohr (ear)	Kinn (chin)	Haare (hair)
street vehicles	Auto (car)	Lastwagen (truck)	Motorrad (motorcycle)	Kutsche (carriage)	Bus (bus)	Traktor (tractor)
upper boddy clothing	Mantel (coat)	Jacke (jacket)	Pullover (sweater)	Hemd (shirt)	T-Shirt (t-shirt)	Bluse (blouse)

APPENDIX B: VOT ANALYSES INCLUDING AGE AS COVARIATE

Table B1. GLMM Assessing Semantic Interference with Age as Covariate

	Response Times			
Predictors	*Estimates*	*SE*	*Statistic*	*p*
Intercept	1078.39	102.88	10.48	< .001
picture type: related vs. unrelated	34.91	15.08	2.31	.021
set size: 4 vs. 3	−4.89	13.59	−0.36	.719
set size: 5 vs. 3	−6.26	15.78	−0.40	.692
rel vs. unrel × 4 vs. 3	15.12	27.89	0.54	.588
rel vs. unrel × 5 vs. 3	2.41	32.39	0.07	.941
age	5.90	1.89	3.12	.002

Table B2. GLMM Assessing Semantic Interference across Item Repetitions with Age as Covariate

	Response Times			
Predictors	*Estimates*	*SE*	*Statistic*	*p*
Intercept	1138.49	7.88	144.50	< .001
picture type: related vs. unrelated	35.69	4.95	7.21	< .001
picture repetition	−61.80	3.86	−16.00	< .001
picture type × repetition	4.70	5.76	0.82	.414
age	5.04	1.13	4.45	< .001

APPENDIX C: FIXATION DURATIONS

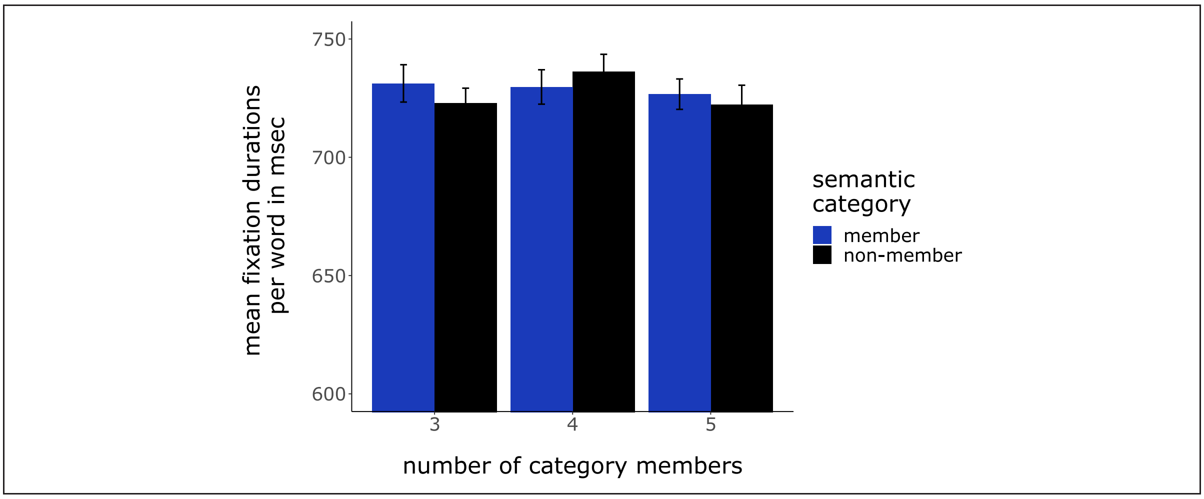

Figure C1. Mean fixation durations per word for category members versus nonmembers.

Table C1. GLMM Assessing Fixation Durations on Category Members versus Nonmembers with Age as Covariate

	Fixation Durations			
Predictors	*Estimates*	*SE*	*Statistic*	*p*
Intercept	860.22	1.51	571.44	< .001
word type: category member vs. nonmember	2.51	1.83	1.37	.169
set size: 4 vs. 3	4.44	1.03	4.29	< .001
set size: 5 vs. 3	0.23	1.22	0.19	.850
member vs. nonmember × 4 vs. 3	−15.05	1.08	−13.96	< .001
member vs. nonmember × 5 vs. 3	−1.75	3.63	−0.48	.631
age	−2.52	0.41	−6.13	< .001

APPENDIX D: CORRELATIONS WITH CLINICAL LINGUISTIC MEASURES

Table D1. Correlations between Experimental Variables and Linguistic Test Scores

Linguistic Test Score	*Experimental Effect*	*Spearman's Rho*	*p Value*
LEMO: Reading	Δ fixation durations	0.235	.229
	semantic interference	−0.093	.637
LEMO: Synonyms	Δ fixation durations	0.244	.21
	semantic interference	−0.207	.29
AAT: Naming	Δ fixation durations	−0.218	.318
	semantic interference	−0.26	.231
fluency: animals	Δ fixation durations	−0.12	.586
	semantic interference	−0.235	.281
NVST	Δ fixation durations	0.463	**.013**
	semantic interference	0.099	.617

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Diversity in Citation Practices

A retrospective analysis of the citations in every article published in this journal from 2010 to 2020 has revealed a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience* (*JoCN*) during this period were M(an)/M = .408, W(oman)/M = .335, M/W = .108, and W/W = .149, the comparable proportions for the articles that these authorship teams cited were M/M = .579, W/M = .243, M/W = .102, and W/W = .076 (Fulvio et al., *JoCN*, 33:1, pp. 3–7). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance.

Notes

1. We use this unspecific term to differentiate from semantic dementia, which is usually subsumed under the primary progressive aphasia umbrella. We do not limit the term "typical aphasia" to the etiology of stroke.
2. Vice versa: If a participant showed a lesion in one single voxel only, the performance deficit could be precisely ascribed to this voxel.

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3 Summary

Zusammenfassung der Arbeit

Dissertation zur Erlangung des akademischen Grades

Dr. rer. med.

Semantic context effects on language production in neurotypical speakers and people with aphasia

eingereicht von

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The complex process of fluent and effortless language production has been the subject of psycho- and neurolinguistic research for many years. Picture naming experiments as an approximation for natural speech settings have been used to investigate which factors influence speed and accuracy when retrieving the name of an object we want to interact with (Glaser, 1992). Experimental set-ups such as the picture-word-interference (PWI) paradigm have shown that the semantic context of target picture naming is an important factor either inhibiting

or facilitating retrieval. Specifically, presenting semantically related context pictures or words belonging to the same semantic category (e.g., cat and dog for the category animals) in the PWI paradigm slows down picture naming and results in more erroneous responses, both in speakers with intact language production abilities as well as in people with language impairments (for a review see Bürki et al., 2020). Importantly, these effects are informative of the semantic and lexical processes involved in word production. Yet, the interaction of these processes and their underlying neural mechanisms are not yet fully understood.

In my thesis, I aim to contribute to a better understanding of the interaction of semantic processing and lexical selection in neurotypical speakers and people with aphasia. In my first study (van Scherpenberg et al., 2020), I implemented a novel multi-word interference paradigm combined with eye tracking to assess semantic activation and lexical selection in the presence of distracting information. Having introduced the novel paradigm in a cohort of healthy participants, in my second study (van Scherpenberg et al., 2021) I focused on participants with acquired language impairments after left-hemispheric lesions of the language network. In addition to behavioral measures of picture naming speed and accuracy, I investigated lesion behavior correlations to shed light on the neural underpinnings of semantic and lexical processes.

A considerable number of studies on language production processes has accumulated evidence for the assumption that lexical selection is dependent on the activation of competing alternatives (Abdel Rahman & Melinger, 2009, 2019; Bloem et al., 2004; Caramazza, 1997; La Heij et al., 2006; Melinger & Abdel Rahman, 2013). In the PWI paradigm, this lexical competition is induced by auditorily or visually presented word distractors. In my first study, “A novel multi-word paradigm for investigating semantic context effects in language production“, I adapted the classical PWI paradigm to carry this assumption one step further. We assessed whether directly increasing the number of lexical competitors presented before picture onset would increase their inhibitory effect on naming. Previous research had indicated that manipulating activation strength of lexical competitors indirectly through semantic neighborhood density (Rabovsky et al., 2016) or semantic similarity (Rose et al., 2018; Vigliocco et al., 2002) affects picture naming latencies. Here, we hypothesized that, for example, 5 distractor words would interfere more strongly with picture naming than 4 distractor words (and 4 more than 3), significantly slowing down naming latencies (see also Abdel Rahman & Melinger, 2008). Testing our manipulation, we found a significant overall semantic interference effect from these multiple distractor words. However, in contrast to our hypothesis, naming latencies did not increase linearly dependent on the number of distractor words. This was the case for both neurotypical participants *(Study 1)* as well as people with aphasia *(Study 2)*. Our findings are therefore more supportive of the idea that once a threshold is reached and the lexical network is "swinging", additional semantic competitors do not further affect the selection mechanism beyond the already triggered lexical competition (Abdel Rahman & Melinger, 2009; Piai et al., 2012).

In addition to providing novel evidence on the effect of multiple distractor words on picture naming, our paradigm allowed us to explicitly assess processing of the visually presented semantic context, using eye tracking. Here we were able to show that our neurotypical participants fixated on categorical competitor words longer than on the remaining unrelated words. We suggest that this preference indicates "semantic competence" resulting in preferential processing of category members *(Study 1)*. However, longer fixation durations on category members did not correlate with longer naming latencies, again supporting the notion that increased attention to or processing of lexical competitors does not further augment their inhibitory effect on lexical selection. Interestingly, most recent evidence from a cohort of neurotypical older adults (aged 60 – 70) with the same paradigm shows facilitatory effects on picture naming when categorically related distractor words are fixated longer compared to unrelated words. These findings (Beese, van Scherpenberg, et al., manuscript in preparation) indicate that older adults may in fact profit from explicit processing of category members to draw attentional resources for lexical selection.

Lesions to the language network are known to drastically effect language production at different processing steps, dependent on impairment type and lesion site. In my second study, "Semantic interference through multiple distractors in picture naming in people with aphasia", we implemented our paradigm in a clinical participant cohort to further tap into the interaction of semantic and lexical processing steps. In this participant group, the multiple distractor words elicited a numerically even stronger semantic interference effect compared to the neurotypical group. However, interestingly, explicit acknowledgement of the categorical relationship between these distractor words was not reflected in the fixation pattern – in other words, category members were fixated equally long compared to non-members. Notably, this pattern correlated with lesions in the Anterior Temporal Lobe (ATL), that is, participants with lesions in this area were less likely to differentiate between these word types when exploring the word set. These findings provide relevant insights into several aspects of (impaired) language production. On the one hand, they support the assumption that semantic information may not need to be explicitly acknowledged in order to induce interference. Instead, implicit, automatic processing when reading the distractor words seems to spread enough semantic activation to the network to prompt competition between lexical alternatives. This is in line with findings from other experimental paradigms assessing semantic context effects on language production, in particular the continuous naming paradigm. Here, several exemplars of semantic categories are named within a seemingly unrelated sequence of pictures. Even though the semantic relationship between the pictures is not apparent due to their seemingly random appearance, naming latencies have been shown to increase linearly for each additional category member to be named (cumulative semantic interference, CSI) (Belke & Stielow, 2013; Howard et al., 2006; Oppenheim et al., 2010; Schnur, 2014). Our novel paradigm allows to assess this semantic activation more explicitly, by tracking the participants' eye movements while they explore the semantic context.

On the other hand, our findings support previous research on the involvement of the ATL as a "semantic hub" in semantic network activation (Chen et al., 2017; Mesulam et al., 2013; Pobric et al., 2007). In our paradigm, decreased "semantic competence", that is, less differentiation between category members and non-members in the participants' eye movements, correlated with lesions in the ATL, even though participants did not show semantic memory deficits according to clinical tests. Studies investigating semantic processing in participants with semantic memory impairments such as Semantic Dementia (and primary atrophy in the ATL) showed that these individuals were less able to distinguish between category members and unrelated picture foils compared to neurotypical participants (Faria et al., 2018; Seckin et al., 2016). It will be an exciting question for future research to investigate people with clinically apparent semantic memory deficits to find out whether they show a similar pattern of semantic processing revealed by eye movements to that in our paradigm. Research along this line could further clarify the debate whether an intact semantic network is needed for a "swinging" lexical network inhibiting lexical selection by competition.

In an ongoing collaboration project (Pino, van Scherpenberg, et al., in preparation) we are tapping into this research question from a different point of view. Here we are comparing distractor-induced semantic interference as elicited by the PWI paradigm, and CSI in the continuous naming paradigm in one cohort of participants with lesions to the language network. Thereby we are able to directly relate these two types of context effects within-participant, investigating the role of language impairments on (implicit) semantic network activation and competitor inhibition during naming.

In a recently completed project we were able to replicate the CSI effect both with overt spoken as well as typewritten responses collected through the participants' web-browsers (Stark, van Scherpenberg, et al., 2021). Thereby we have established an easy-access route for collecting large datasets on reaction-time sensitive language production research also with participants with language- or other disorders hindering in-person testing.

Together, with the studies summarized in this dissertation and the collaboration projects outlined above, my work has contributed important methodological and conceptual insights into semantic context effects in healthy and impaired language production.
Our novel multi-word paradigm offers an exciting new method to assess the interaction of semantic and lexical processing by combining eye tracking and picture naming as two behavioral measures within one paradigm. Establishing a measure of categorization reflected in eye movements, which we have coined "semantic competence", allows to assess explicit acknowledgment of the semantic relationship within the semantic context. This can be directly linked to lexical retrieval amongst competing information, by assessing speed and accuracy in the consecutive picture naming task. By varying the type of semantic relationship within the visually presented stimulus array or its modality (e.g., pictures instead of words), the paradigm can be flexibly adjusted to assess various semantic context effects in neurotypical and clinical populations.

Finally, our ongoing research in which we, for the first time, compare PWI and CSI within one group of people with aphasia, can clarify the relationship of these two well established effects which have helped shaping our understanding of language production processes.
Last but not least, our replication of semantic interference effects in web-based settings promises highly interesting opportunities for transferring language production experiments to online settings, thereby increasing and diversifying participant populations.

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Author contributions to the publication

"A novel multi-word paradigm for investigating semantic context effects in language production"

By Cornelia van Scherpenberg (CvS), Rasha Abdel Rahman (RAR), Hellmuth Obrig (HO); Plos One, 2020

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Declaration of Authenticity

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Datum Unterschrift

List of publications

Accepted and in print

Stark, K.*, **van Scherpenberg, C.***, Obrig, H., & Abdel Rahman, R. (2022). Web-based language production experiments: Semantic interference assessment is robust for spoken and typed response modalities. *Behavior Research Methods*. https://doi.org/10.3758/s13428-021-01768-2

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In preparation

Beese, C.*, **van Scherpenberg, C.***, Martin, S., Hartwigsen, G. & Obrig, H. Age differences in semantic inhibition during word retrieval.

Pino, D.*, **van Scherpenberg, C.***, Döring, A., Lorenz, A., Regenbrecht, F. & Obrig, H. Distractor-induced vs. cumulative semantic interference: comparative insights from aphasia.

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van Scherpenberg, C., Abdel Rahman, R., & Obrig, H. (2019) Picture-word interference – can the effect be modulated? An eye tracking study. *61. Tagung experimentell arbeitender Psychologen*, London, UK.

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Posters

Stark, K.*, **van Scherpenberg, C.***, Obrig, H. & Abdel Rahman, R. (2021). Browser-based cumulative semantic interference with overt verbal vs. typewritten responses. *46. Jahrestagung Psychologie und Gehirn*.

van Scherpenberg, C., Abdel Rahman, R., Regenbrecht, F. & Obrig, H. (2019). Neues Wort-Bild- Interferenzparadigma mit mehreren Distraktoren zur Untersuchung von semantischen Kontexteffekten bei sprachgesunden Probanden und Personen mit Aphasie. *Jahrestagung der Gesellschaft für Aphasieforschung und -behandlung*, Leipzig.

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