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Structuring language: Contributions to the neurocognition of syntax

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The research reported in this thesis was carried out at the Max Planck Institute for Psycholinguistics, in collaboration with the Donders Institute for Brain, Cognition and Behaviour, Centre for Cognitive Neuroimaging, Radboud University Nijmegen.

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Structuring language

Contributions to the neurocognition of syntax

Een wetenschappelijke proeve op het gebied van de Sociale Wetenschappen

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Chapter 1

Introduction and outline

Communicating with others is crucial in our language-oriented society. A speaker starts with a communicative intention or a message representation that she wants to communicate to a listener. Over several processing stages, this intention is converted into a sequence of sounds which are articulated. The listener in turn receives this stream of auditory information and has to retrieve its meaning and the intention of the speaker.

Successful communications relies on more than just the production and understanding of single words. The same words can be combined to yield different meanings: *The woman strangles the man* is not the same as *The man strangles the woman.* A crucial ability of speakers as well as listeners is processing combinations of words, or sentences.

For a listener, recognizing words in an incoming stream of speech sounds is merely the starting point of *retrieval* and *unification* processes (Hagoort, 2005; Jackendoff, 2002). Information we have learned about specific single words, e.g. how words sound, how they are written, their meaning and syntactic information associated with the word, is stored in long-term memory. From long-term memory, or from what psycholinguists call our mental lexicon, we retrieve the information about single words. These building blocks of information are used during syntactic and semantic unification processes, when the listener derives a syntactic structure and a meaning interpretation for a combination of words or a sentence. A speaker completes the same processes in reversed order. This again requires the *retrieval* of building blocks from the mental lexicon and semantic/conceptual as well as syntactic *unification*. In this dissertation, I will focus on the retrieval and combination of syntactic information: syntactic processing.

Syntactic processing

Syntactic processing, or specifying the syntactic relations between words in the sentence, is a core process during both the production and comprehension of language. Speakers have to construct and listeners have to deconstruct the syntactic structures of sentences. I will investigate this process more closely and look into the behavioural (Chapters 2 and 3) as well as neuronal reflections (Chapters 4, 5 and 6) of syntactic processing, during speaking and during listening. In Chapter 7 I will further discuss the findings reported in this dissertation.

Why syntactic priming?

Syntactic priming effects are a useful vehicle to investigate syntactic processing. Syntactic priming refers to the facilitated processing of a syntactic structure when it is the same as the syntactic structure of a preceding sentence. Behavioural reflections of this facilitation during speaking are an increased likelihood to produce the same syntactic structure and/or an increased speed of producing the same structure. This is referred to as syntactic priming effects on response tendencies and syntactic priming effects on response latencies respectively.

Syntactic priming likely serves multiple functions (Ferreira & Bock, 2006). Firstly, we implicitly learn syntactic structures, after which we produce them more often (Chang, Dell, & Bock, 2006). This outcome has been studied extensively and is described well in the literature. However, not all syntactic structures are equally frequent. The message that a girl is kissing a boy could be expressed in a sentence with an active syntactic structure *("The girl kissed the boy"),* or in a sentence with a passive syntactic structure *("The boy was kissed by the girl").* Active sentences, however, are much more frequently used than passives sentences. In Dutch, the proportion of passive transitive sentences is only about 8% (Cornelis, 1996). Interestingly, we seem to 'learn' more from an experience with an infrequent syntactic structure. Our response tendencies are influenced to a large extent when an infrequent structure - like a passive sentence - is syntactically primed. The influence on the response tendencies is much larger than when a frequent structure is syntactically primed. This fascinating characteristic of syntactic priming has been termed the inverse frequency effect (Ferreira & Bock, 2006). In other words, syntactic processing takes the frequency of alternative syntactic structures into consideration and benefits the unfrequent or underrepresented alternative; syntactic processing implements 'affirmative action' (Ferreira, unpublished). This way, the less frequent syntactic structures (the minority group) will prevail and be included in our language use. Keeping some syntactic flexibility in place has advantages, as it allows more nuanced communication.

It has also been suggested that the repetition of syntactic structures promotes production ease and fluency. However, the effects of syntactic priming on response latencies are largely understudied in the literature. This is surprising, given that three decades have elapsed since Levelt and Kelter (1982) suggested that the function of syntactic persistence in natural speech is to promote the fluency and speediness of sentence generation and to reduce processing costs for the speaker: *"… reusing previous discourse elements has the additional function of facilitating the fluency of the formulation process itself. It may require less effort to reuse available surface materials wherever possible than to generate speech every time anew from a semantic base" (p.105, Levelt & Kelter, 1982).*

A third function of syntactic priming mentioned in the literature is correspondence or alignment in dialogue (Garrod & Pickering, 2009). Dialogue is a 'joint action' during which the participants of the dialogue strive to align their understanding and representation of the situation (i.e. the situation model). Alignment occurs at several levels. For instance, speakers start using the same words. Syntactic representations also take part in this: speakers start using the same syntactic structures to describe comparable aspects of the situation (Branigan, Pickering, & Cleland, 2000; Garrod & Pickering, 2009).

In this dissertation I will focus on the first two functions mentioned in this overview. In Chapter 2 and 3 of this dissertation I will study whether repeated structures are indeed produced faster. I will furthermore discuss the relationship between on the one hand fluency effects reflected in response latencies and on the other hand learning or affirmative action effects reflected in response tendencies. I will argue that the relationship between these two functions is determined by the frequency of syntactic structures. In Chapter 2, I will investigate syntactic priming effects of transitive sentences in Dutch. For all transitive verbs, the passive construction is preferred over the active construction. In Chapter 3, I will look into syntactic priming effects for ditransitive sentences in German. Interestingly, for some ditransitive verbs the prepositional object construction is preferred *("The man sells the painting to the woman")* while for other verbs the double object dative construction is preferred *("The man shows the woman the painting").*

Thus, while in Chapter 2 I will investigate the role of frequencies or preferences at the more general level of an entire category of verbs, in Chapter 3, I will zoom into the role of syntactic preferences at the level of individual verbs. By investigating whether syntactic information stored for specific lexical items determines the processing of sentence structures, I will tap into the relationship between lexical and syntactic processing.

Taking syntactic priming into an fMRI scanner

Behavioral syntactic priming effects can serve to answer many questions about syntactic processing, but some questions can only be answered by studying syntactic priming effects at the neuronal level.

In the Chapter 4, 5 and 6 of this dissertation, I will use a neuroimaging technique called functional Magnetic Resonance Imaging (fMRI). With this technique, we can measure which brain regions receive more oxygen-rich blood while we challenge the brain with a specific task. An increased level of blood oxygenation in a particular brain region indicates that this region is more active or more engaged, due to the presence of the task. I will use a specific application of fMRI called fMRI adaptation. The Blood Oxygen Level Dependent (BOLD) response of the brain is sensitive to the repetition of stimuli (Grill-Spector & Malach, 2001; Henson, 2003). Usually, the neural response is reduced when a stimulus is repeated; this is called *repetition suppression*. For instance, when you see a picture of a red umbrella twice, the BOLD-response in brain regions sensitive to red umbrellas may be reduced the second time the red umbrella is shown. The change in the BOLD-signal is only affected by the specific feature of the stimulus which is repeated. If you first see a red umbrella and then a blue umbrella, only regions sensitive to the shape of the umbrella, not its color, will show a reduced BOLD-response. This way, fMRI adaptation paradigms make it possible to indentify very specialized brain functions. Sometimes, the neural response is enhanced when a stimulus is repeated; this is called *repetition enhancement*. Cases in which repetition enhancement is likely to occur are e.g. when a stimulus is highly unfamiliar, or when special attention is given to the repeated stimulus (Segaert, Weber, de Lange, Petersson, & Hagoort, submitted). There is some controversy regarding the exact neural mechanism(s) underlying these BOLD-response changes, making it difficult to predict exactly when the brain shows a reduced versus an enhanced response to repeated stimuli (Grill-Spector, Henson, & Martin, 2006; Henson, 2003; Krekelberg, Boynton, & van Wezel, 2006; Segaert, et al., submitted).

The neurobiology of syntactic processing

Several neuroimaging studies have already investigated the neurobiological infrastructure of syntactic processing (e.g. Haller, Radue, Erb, Grodd, & Kircher, 2005; Indefrey, et al., 2001; Menenti, Gierhan, Segaert, & Hagoort, 2011; Noppeney & Price, 2004; Snijders, et al., 2009). These studies mainly found that left inferior frontal regions and left temporal regions of the brain are involved in syntactic processing, during speaking and during listening. Previous work also supports a division of labor between the functional contributions of these two brain regions. While left middle temporal regions support the retrieval of lexical-syntactic information from memory, left inferior frontal regions support the unification of this information into multi-word utterances (Hagoort, 2003, 2005; Snijders, et al., 2009). In this dissertation I will study the neurobiological infrastructure of syntactic processing further. Using fMRI adaptation, I will zoom in on some specific characteristics of this process.

Syntactic processing... Shared? Lexicalist? Implicitly learned?

In Chapter 4 of this dissertation, I will investigate whether the neuronal infrastructure for coding and processing syntactic representations is shared between language production and language comprehension. This can be tested by comparing fMRI adaptation effects for the repetition of syntactic structures within and between processing modalities. If the production and comprehension modality share the neuronal substrate for syntactic processing then processing syntax in one modality should lead to adaptation effects in the other modality. While within-modality syntactic adaptation effects in comprehension and production show that the same brain regions are involved, only comparable between-modality adaptation effects indicate that the neuronal populations within these regions are shared. Evidence for a shared neuronal infrastructure provides support for the idea that between processing modalities there is a shared cognitive system with shared representations (Pickering & Garrod, 2004) and/or processes manipulating these representations (Kempen, 2000).

I proceed to investigate, in Chapter 5, whether the neuronal activity in brain regions subserving syntactic processing reveals a "lexical boost" of syntactic priming effects. Syntactic priming effects can be strengthened by repeating not only the syntactic construction but also the lexical item that functions as head of that construction: the so-called lexical boost. Findings demonstrating the influence of lexical factors on syntactic priming, such as the presence of a "lexical boost" due to verb repetition, provide an argument for so-called lexicalist grammar frameworks (Jackendoff, 2002). In these frameworks, the distinction between traditional grammar rules and lexical items is blurred or has disappeared completely. The influence of the lexical boost on neuronal syntactic repetition effects is tested by measuring the extent of fMRI adaptation to repetition of verb-headed syntactic constructions with vs. without repetition of the head verb.

In Chapter 6, I will investigate the longevity of syntactic repetition effects in the brain. More specifically, are fMRI adaptation effects to repeated syntactic structures also present when the repeated syntactic structure does not immediately follow the first production of this structure? This would provide support for the idea that the use of syntactic procedures entails implicit learning (Chang, et al., 2006; Chang, Dell, Bock, & Griffin, 2000). Put another way, when a speaker uses a syntactic structure, he or she gains experience in expressing a message with that particular syntactic structure. The consequence of this adjustment is that a previously used syntactic structure is more likely to be repeated. Adjustments due to implicit learning should be relatively long-lasting.

Collectively, the results of the studies reported in this dissertation provide insight into the workings of syntactic processing and further constrain neurocognitive theories of this process.

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Chapter 2

A paradox of syntactic priming: Why response tendencies show priming for passives, and response latencies show priming for actives

Speakers tend to repeat syntactic structures across sentences, a phenomenon called syntactic priming. Although it has been suggested that repeating syntactic structures should result in speeded responses, previous research has focused on effects in response tendencies. We investigated syntactic priming effects simultaneously in response tendencies and response latencies for active and passive transitive sentences in a picture description task. In Experiment 1, there were priming effects in response tendencies for passives and in response latencies for actives. However, when participants' pre-existing preference for actives was altered in Experiment 2, syntactic priming occurred for both actives and passives in response tendencies as well as in response latencies. This is the first investigation of the effects of structure frequency on both response tendencies and latencies in syntactic priming. We discuss the implications of these data for current theories of syntactic processing.

Adapted from: Segaert, K., Menenti, L., Weber, K., & Hagoort, P. (2011). A paradox of syntactic priming: Why response tendencies show priming for passives, and response latencies show priming for actives. PLoS One, 6(10), e24209. doi:10.1371/journal.pone.0024209.

Introduction

We repeat all kinds of linguistic units when we speak: words, phrases and even syntactic structures (Miller & Weinert, 1998). The tendency to use similar syntactic structures across sentences is called structural or syntactic priming (Bock, 1986). When speakers produce a given structure in one sentence on a prime trial (e.g., a passive sentence: '*The boy is kissed by the girl*'), the chance of producing the same structure on a subsequent, target trial increases (e.g., '*The woman is hugged by the man*').

Syntactic priming provides a window into syntactic processing and therefore it allows testing different theories. There are two influential theories of syntactic processing in language production. The implicit learning theory (Chang, Dell, & Bock, 2006; Chang, Dell, Bock, & Griffin, 2000) proposes that syntactic persistence occurs through implicit error-based learning. This theory argues for a system in which sentence structures are assembled through the construction of abstract syntactic frames into which lemmas are then inserted. Since implicit learning takes place outside the mental lexicon, this theory does not predict syntactic priming effects to be boosted by lexical repetition. An alternative theory is the residual activation theory (Cleland & Pickering, 2003; Pickering & Branigan, 1998) which explains syntactic persistence in terms of a short-term memory or activation effect of syntactic frames which are tied to the lexicon and determine word order. This entails that syntactic processing is lexically driven and that syntactic priming effects will be boosted when the head of the construction (e.g., the verb for transitive sentences) is repeated.

Numerous language production studies have investigated syntactic priming effects for transitive sentences by measuring response tendencies, i.e. the frequency of speakers choosing one structure over an alternative structure on target trials. These studies found evidence for syntactic priming of transitives in both English (Bock, 1986; Bock, Dell, Chang, & Onishi, 2007; Bock & Griffin, 2000; Bock & Loebell, 1990; Bock, Loebell, & Morey, 1992; Boyland & Anderson, 1998) and Dutch (Bernolet, Hartsuiker, & Pickering, 2009; Hartsuiker & Kolk, 1998). However, while these priming effects have been shown repeatedly for passive sentences, comparable effects for active sentences are either absent (experiment 2 and 3 of Bock, 1986; Bock & Loebell, 1990; Hartsuiker & Kolk, 1998) or smaller than for passives (Bernolet et al., 2009; experiment 1 of Bock, 1986). A ceiling effect in the baseline frequency of producing actives may explain the absence or weakness of syntactic priming for actives in response tendencies: in Dutch written discourse, the proportion of active transitives is about 92% and, in English, about 88% (Cornelis, 1996).

Syntactic priming effects for active transitives may, however, be revealed in response latencies, which may not suffer from such a ceiling effect. Levelt and Kelter (1982) suggested that the function of syntactic persistence may be to promote fluency and speed of sentence production and to reduce processing costs for the speaker, but very few studies have investigated priming effects in response latencies (for datives: Corley & Scheepers, 2002; for noun phrases: Smith & Wheeldon, 2001; Wheeldon & Smith, 2003).

The implicit learning theory of syntactic priming (Chang et al., 2006; Chang et al., 2000) is a theory about structure selection and does not make specific predictions about response latency effects. The residual activation theory as put forward by Pickering and Branigan (1998) does also not make specific predictions about response latency effects. However, others have derived the prediction from this model that response latency effects should mirror response tendency effects (Corley & Scheepers, 2002). This assumes that the activation in syntactic units determines not only choice but also selection speed. In the case of transitives, activation in a syntactic unit influences word order by activating the agent or patient as subject of the sentence. Residual activation makes it more likely for the same units to reach the selection threshold and be used again, changing response tendencies on target trials. Under the assumption that response tendencies and response latencies are both outcomes of the same mechanism, thresholds are reached faster when specific structures are repeated, resulting in faster response latencies.

In the present study we investigated syntactic priming of transitives in Dutch spoken language production using a picture description paradigm. We simultaneously measured response tendencies and response latencies. In Experiment 1 we explored the hypothesis that actives can be syntactically primed and that syntactic repetition of actives would result in faster response latencies. We hypothesized that in response tendencies there would an apparent syntactic priming effect for passives while the effect for actives may be obfuscated due to a ceiling effect in the baseline frequency of actives. We expected to see syntactic priming effects for actives as well as passives in speech onset latencies. If, however, the lack of response tendency effects for actives is not due to a ceiling effect but due to actives being less prone to syntactic priming, effects for actives should also be absent in the response latencies.

Experiment 1

Materials and Methods

Participants

Thirty native Dutch speakers (15 male/15 female, mean age of 23 years with SD 3.9) gave written informed consent prior to the experiment (as approved by the local ethics committee Commissie Mensengebonden Onderzoek Region Arnhem-Nijmegen) and were compensated for their participation.

Materials

Our stimulus pictures depicted 36 transitive events such as *kissing, helping,* or *strangling* with the agent and patient of this action (Appendix 2.1). The pictures elicited transitive sentences. Each event was depicted with two pairs of adults and one pair of children. There was one male and one female actor in each picture, and each event was depicted with each of the two actors serving as the agent. The position of the agent (left or right) was randomized.

Each transitive picture had three versions: one grayscale version and two color-coded versions with a green and a red actor (which elicited either an active or passive transitive - see task description). Fillers elicited either intransitive sentences, depicting events such as *running, singing, bowing* with one actor (in grayscale, green or red) or locative sentences, showing events such as *standing, sitting, lying* with either two objects or one actor and one object (either grayscale or color-coded to elicit a locative state or a frontal locative).

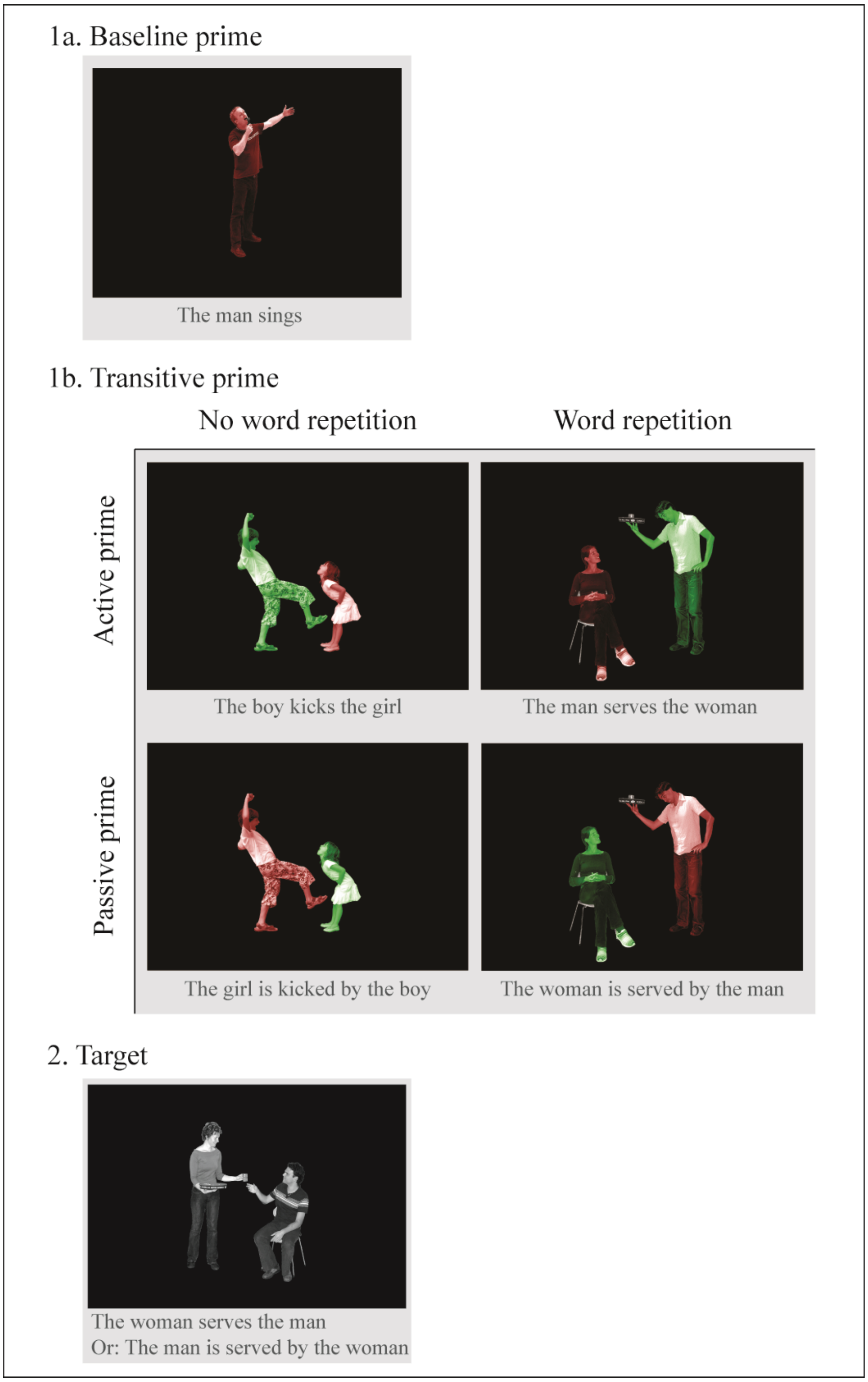

Figure 1. Design Experiment 1. Each trial consisted of a color-coded prime (1a. or 1b.) and a grayscale target (2.). On baseline trials (1a. followed by 2.) primes were intransitive or locative sentences, so that we could measure the baseline frequency of using active and passive transitives. On transitive priming trials (1b. followed by 2.) we measured the syntactic priming effect for transitive sentences in four conditions. Transitive primes could be active (top row) or passive (bottom row). Furthermore, there could be no word repetition (left column) or word repetition (right column) between prime and target. The sentences participants produced responding to the pictures are inserted for clarity.

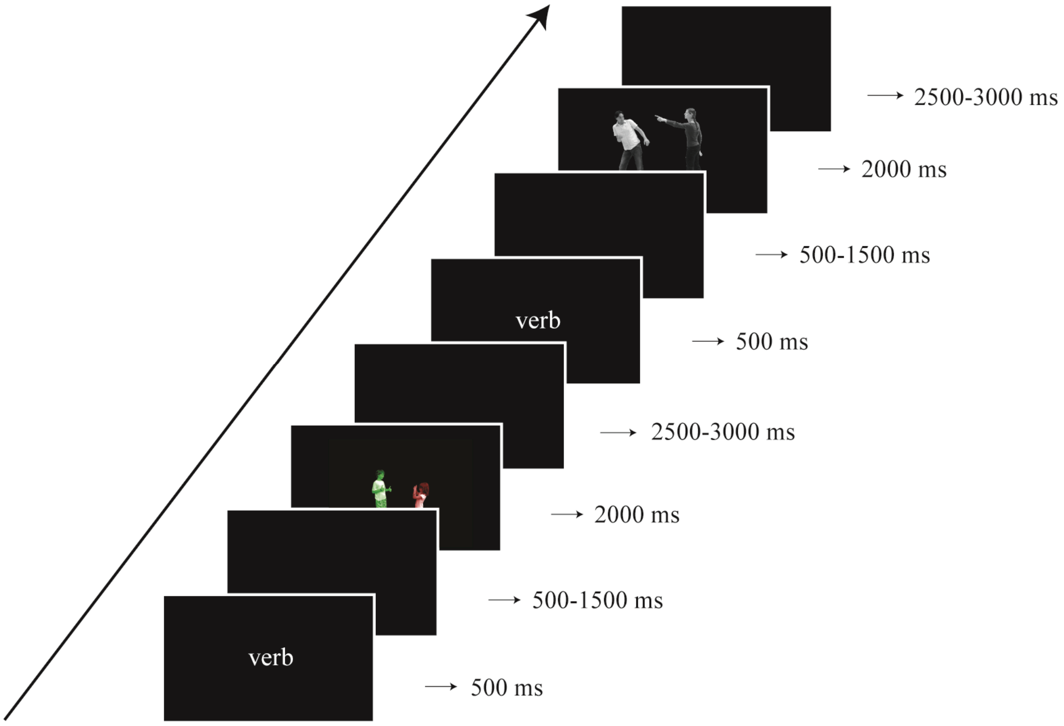

Figure 2. Procedure Experiment 1 and 2. Each trial consisted of the following events: a verb was presented in its infinitive form and after a jittered interval the prime picture was presented. After a jittered interval a verb was again presented, followed by the next jittered interval and a target picture. After another jittered interval the next trial started.

We pretested the materials to verify whether the depicted actions were clear and to measure which verb was most commonly used to describe each action. In the experiment this verb was presented preceding the picture.

Task and design

The task and design of this experiment were adapted from Menenti et al. (Menenti, Gierhan, Segaert, & Hagoort, 2011) and are illustrated in Figure 1. Participants were instructed to describe pictures with one sentence, naming the green actor before the red actor if the actors were depicted in color. If the actors were not depicted in color then participants did not have to pay attention to the order of mentioning the two actors and could therefore produce either an active or a passive sentence.

Each trial consisted of a prime followed by a target. Primes were pictures in which actors were color-coded for the order of precedence in the sentence, allowing us to manipulate the syntactic structure participants would produce (example 1a and 1b in Figure 1). A grayscale target eliciting a transitive sentence immediately followed the prime (example 2 in Figure 1).

There were two types of trials: baseline trials and transitive priming trials. On baseline trials, primes were intransitive or locative sentences (1a in Figure 1) so that we could measure the baseline frequency of producing active and passive transitives on subsequent targets. On transitive priming trials we measured the syntactic priming effect in four conditions (1b in Figure 1), resulting from a manipulation of prime structure (active versus passive), fully crossed with a manipulation of word repetition (no word repetition versus word repetition between prime and target). With the latter manipulation we investigated the influence of repeating words on syntactic priming effects. Note that in the word repetition conditions not only the verb, but also the actors are repeated. Preserving word order in these conditions implies reversing the thematic roles in the sentence. Syntactic priming effects are then unaffected by thematic role priming.

As in Menenti et al. (2011), there were also successive transitive sentences for which words as well as sentence-level meaning were identically repeated. Since these trials are not relevant for the issues at stake here, they are not included in the analysis (including these trials in the analysis does not change the effects or their significance levels).

Intransitive ('The man sings') and locative ('The bottle stands on the table') sentences served as fillers, such that over the whole experimental list half of the items elicited transitives and half of the items did not. In total, each experimental list contained 72 baseline trials and 24 trials in each of the 4 transitive priming conditions. We generated counterbalanced lists so that each target picture occurred once with a baseline prime, once with an active prime and once with a passive prime across each triplet of experimental lists.

Procedure

Participants received ten practice trials at the beginning of the experimental session. The actual experiment lasted 50 minutes. Figure 2 illustrates the sequence of events on each trial. Participants' responses were recorded and a voice key measured response latencies from picture presentation.

Responses were manually coded as active or passive. Target responses were considered for analysis only if 1) the correct structure was used on the prime trial and 2) both actors were named accurately and the verb was used correctly on both prime and target trial. Debriefing showed that participants were unaware of the purpose of the experiment.

Results

Response tendencies

We excluded 6.5% (330 out of 5040) of the target responses because they were incorrect (criteria are described under 'Procedure'). We analyzed the responses using mixed-effects logit models (Jaeger, 2008; Pinheiro & Bates, 2000) in R (R Development Core Team, 2009). Coefficient estimates are included in the text only when a full summary is not included in the tables. Target responses were coded as 0 for actives and 1 for passives.

Figure 3a summarizes the proportion of passive responses. When we exclude the data from the baseline condition, we can fit a model with the predictors 'Prime structure' and 'Word repetition'. We modeled random subject and item effects by including a random intercept and random slopes of 'Prime structure' and 'Word repetition' for

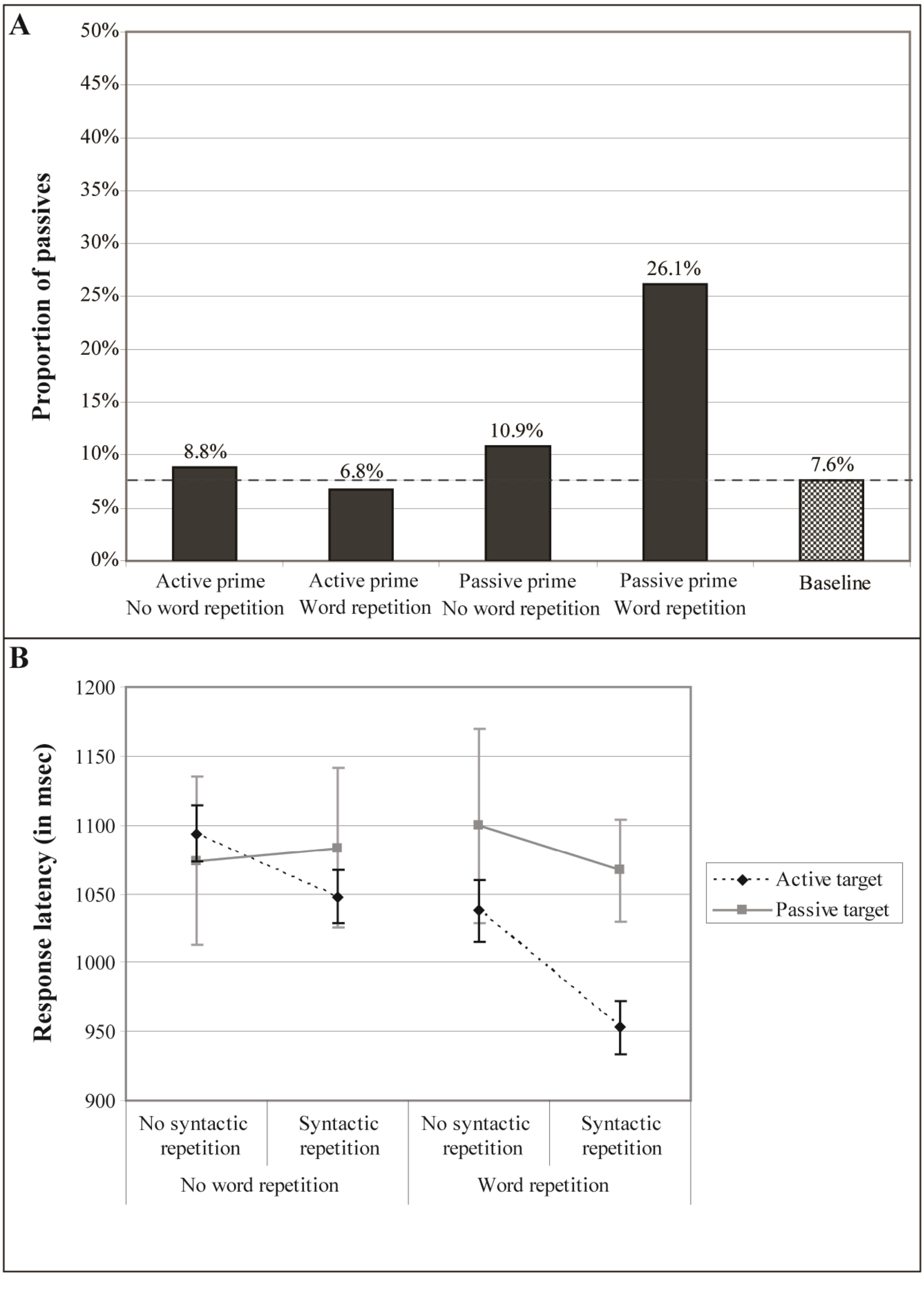

Figure 3. Results Experiment 1. A) Response tendency results: the proportion of passive transitives is illustrated for each condition, and **B) Response latency results:** mean response latencies and standard errors for each condition.

subjects and a random intercept for items (this is the maximal random effect structure justified by model comparison). This shows that prime structure (p>.52) did not and word repetition (p<.015) did predict the response tendencies. Also the interaction between prime structure and word repetition predicted the response tendencies (p<.001) (upper part of table 1). To investigate then whether prime structure and word repetition change the response tendencies compared to the baseline proportion of passives versus actives, a predictor with 'Condition' with five levels was added such that the baseline condition was included in the intercept and contrasted with the four conditions which result from fully crossing 'Prime structure' and 'Word repetition' (see bottom of Table 1). Random subject and item effects were modeled by including a random intercept and slope of 'Condition' for subjects and a random intercept for items (this is the maximal random effect structure justified by model comparison). The negative estimate for the intercept indicates that in the baseline condition actives were more frequent than passives. Active primes affected the response tendencies when words were repeated (p<.04) (the negative coefficient indicates that more actives were produced relative to baseline) but not when words were not repeated (p>.09). The response tendencies after an active prime without word repetition differed significantly from the response tendencies after an active prime with word repetition (β=-0.86, p<.006). Passive primes affected response tendencies compared to baseline both when we compared the baseline to passive primes with word repetition (p<.006) and when we compared the baseline to passives primes without word repetition (p<.001) (the positive coefficient indicates that more passives are produced relative to baseline). The response tendencies after a passive prime with word repetition differed significantly from the response tendencies after a passive prime without word repetition (β=-1.08, p<.001).

Response latencies

We excluded 7.5% of correct responses on transitive priming trials (195 out of 2580) because they contained other sounds which triggered the voice key before speech onset or because they were two standard deviations below or above the mean calculated per subject and per condition (Ratcliff, 1993). We created a post-hoc variable 'Syntactic repetition' based on the relationship between prime structure and the structure of the participant's target response. Response latencies were analyzed using mixed-effects linear models (Baayen et al., 2008; Pinheiro & Bates, 2000) in R. (Results are identical when response latencies are analyzed with a repeated-measures ANOVA. Although mixed-effects linear models are less often applied, they are better suited for use with post-hoc variables.)

Figure 3b summarizes the response latency data. The fixed effects of the best model fit for these data are summarized in Table 2. As reference conditions we used: active targets, no syntactic repetition and no word repetition. We included the random intercept and slope of 'Syntactic repetition' and 'Word repetition' for subjects, and the random intercept for items (this is the maximal random effect structure justified by model comparison). Syntactic repetition significantly speeded up response latencies (p<.001), as did word repetition (p<.001). However, the interaction between syntactic repetition and target structure indicates that the effect of syntactic repetition was different for passives than for actives (p<.02). To further investigate this interaction, we constructed the factor 'Condition' with four levels: actives with syntactic repetition, actives without syntactic repetition, passives with syntactic repetition, and passives without syntactic repetition (we estimated this model including the random intercept and slope of 'Word repetition' for subjects, and the random intercept for items). When active

Table 1. Summary of fixed effects in the mixed logit model for the response tendencies in Experiment 1

Predictor	coefficient	*SE*	*Wald Z*	*p*
Excluding the baseline condition (N=2480, log-likelihood=-769)				
Intercept	-3.04	(0.29)	-10.47	<.001 ***
Prime	0.17	(0.27)	0.64	>.52
Word repetition	-0.68	(0.28)	-2.43	<.015 *
Prime by Word repetition	1.91	(0.30)	6.38	<.001 ***
Including the baseline condition in the intercept (N=4710, log-likelihood=-1261)				
Intercept (Baseline)	-3.36	(0.29)	-11.66	<.001 ***
Active prime - No word repetition	0.32	(0.19)	1.73	>.09
Active prime - Word repetition	-0.54	(0.26)	-2.08	<.04 *
Passive prime - No word repetition	0.47	(0.17)	2.74	<.006 **
Passive prime - Word repetition	1.55	(0.26)	5.97	<.001 ***

Table 2. Summary of fixed effects in the mixed linear model for the response latencies in Experiment 1

Predictor	coefficient	*SE*	*t value*	*df*	*Pr(>|t|)*
Intercept	1046.06	57.65	18.14	2020	<.001 ***
Target structure	-0.62	33.09	-0.02	331	>.98
Syntactic repetition	-56.02	17.29	-3.24	331	<.001 ***
Target structure by Syntactic repetition	89.94	39.46	2.28	331	<.02 *
Word repetition	-69.90	16.54	-4.23	331	<.001 ***

Note: N=2385, log-likelihood=-16970. Because Markov chain Monte Carlo sampling (Baayen, Davidson, & Bates, 2008) is not yet implemented for models with random slopes we cannot provide *p*-values based on the posterior distribution. The *p*-values based on the *t*-distribution should therefore only be interpreted with caution. (They were calculated using the package nlme (R Development Core Team, 2009)).

targets without syntactic repetition were included in the intercept and hence contrasted to the other levels of the 'Condition' factor, the analysis showed that the response latencies for active targets were significantly faster with syntactic repetition than without syntactic repetition (β=-56.63, p<.001). When passive targets without syntactic repetition were included in the intercept and contrasted to the other levels of this factor, the analysis showed that for passive targets syntactic repetition did not significantly predict response latencies (β=31.53, p>.4).

Although word repetition significantly speeded up the response latencies, it is noteworthy that there was no three-way interaction between word repetition, syntactic repetition, and target structure: including this interaction did not improve the fit of the model (χ^2_3 = 4.55, p>.21).

Discussion

In Experiment 1 we investigated syntactic priming of transitive sentences in Dutch spoken language production using a picture description paradigm. When syntactic priming is not helped by additional word repetition, we found syntactic priming effects for passives but not actives in the response tendencies and for actives but not passives in the response latencies. In the response tendencies however, word repetition did boost the syntactic priming effect and then not only the effect for passives but also the effect for actives reached significance. Word repetition did not affect priming in response latencies.

These results lend support to the idea that the initial preference ratio of two syntactic alternatives is an important determinant of syntactic priming. Transitive events can be described with active or passive sentences, though crucially, speakers have a strong preference for using actives instead of passives (in Experiment 1 the baseline frequency of actives was 92%). Due to this pre-existing bias, the tendency to select actives is at ceiling, so there is little room for active primes to increase this tendency. An effect of active primes on the response tendencies was however observed when syntactic priming was boosted by word repetition. That actives benefit from syntactic repetition was even more apparent in the response latencies: syntactically repeated actives are produced faster, irrespective of word repetition. This effect of syntactic priming on response latencies for actives had so far not been investigated.

For passives we found syntactic priming effects in response tendencies, replicating previous findings (Bernolet et al., 2009; Hartsuiker & Kolk, 1998). Just like it is the case for actives, for passives the effect of syntactic priming on response latencies had so far not been investigated. We found that there was no latency benefit for repeated passives. Response tendencies and response latencies thus seem to have different sensitivities to the frequency of syntactic constructions. To investigate the role of the relative frequency of syntactic alternatives in determining syntactic priming effects further, we performed a second experiment.

There are in fact other differences between actives and passives than their relative frequency of occurrence. Passives are for instance stylistically marked, or used when there are pragmatic reasons to put the patient of the action in focus. To test whether the results of Experiment 1 are due to the difference between actives and passives in frequency of occurrence per se, or to another difference between actives and passives, we performed Experiment 2. In Experiment 2, we manipulated the relative frequency of occurrence of actives and passives by subjecting participants to a training session before the actual experiment started. During this training session we exposed participants to a pattern of experience with active and passive sentences. In one group the training maintained the pre-existing ratio for actives versus passives, while in another group this was reversed, so that the bias to produce actives instead of passives would become less strong. Kaschak (2007) has demonstrated that such a manipulation affects the base rates of producing the two alternative constructions. If the difference in the effect of syntactic priming on response tendencies versus response latencies for actives and passives in Experiment 1 is indeed due to the difference in their relative frequency, a training session altering the relative frequency should affect the syntactic priming effects. When selection of passives is boosted we expect observable syntactic priming effects for actives as well as passives, both in the response tendencies and in the response latencies.

Another interesting outcome of Experiment 1 was that response tendencies and latencies did not only show differential effects for actives and passives, but also differed in the effect of word repetition on the magnitude of syntactic priming. Word repetition boosted priming effects in response tendencies but not in response latencies. It is important to note that because we aimed to investigate syntactic priming unaffected by thematic role priming in Experiment 1, all words (not just the verb) were repeated. The residual activation theory (Cleland & Pickering, 2003; Pickering & Branigan, 1998) predicts that syntactic priming effects will be boosted when the head of the construction - in the case of transitives this is the verb - is repeated. Therefore, in Experiment 2 we manipulated repetition of the verb when other words in the sentence were not repeated. This allows us to compare our results to those of studies reported in the literature, which traditionally include a manipulation of verb repetition, but not repetition of verb and nouns at the same time.

Experiment 2

In Experiment 2, we tested whether the different syntactic priming effects for actives and passives in response tendencies versus response latencies is indeed due to their relative frequency of occurrence. We submitted one group of participants, the experimental group, to a training session in which they had to produce 90% passive sentences and 10% active sentences. Participants then completed a task similar to that reported in Experiment 1. We expected that the training session alters participants' preference bias such that the selection of passives is boosted. Therefore, in this group we expected to find syntactic priming effects for actives as well as passives, both in response tendencies and response latencies. We submitted another group of participants, a control group, to a training session in which they had to produce 10% passives and 90% actives, maintaining the strong preference bias for actives. We hypothesized that in this group we would replicate the results of Experiment 1: we expected to find a syntactic priming effect for passives in the response tendencies and a priming effect for actives in the response latencies.

Materials and Methods

Participants

Sixty native Dutch speakers (mean age 22 years with SD 3.07; with 30 males divided evenly over control and experimental group) gave written informed consent prior to the experiment (as approved by the local ethics committee Commissie Mensengebonden Onderzoek Region Arnhem-Nijmegen) and were compensated for their participation.

Materials and task

Materials were largely identical to those used in Experiment 1. Additional transitive pictures were created so there were pictures of 41 transitive events in total. The added transitive events were (English translation in brackets): *bekogelen (pelt), kussen (kiss), opmaken (make up), straffen (punish), vervoeren (transport).* Like in Experiment 1, fillers elicited either intransitive sentences or locative sentences. The picture description task was identical to the task in Experiment 1: participants were instructed to describe pictures with one sentence, naming the green actor before the red actor if these were depicted in color. If the actors were not depicted in color then participants did not have to pay attention to the order of mentioning the characters in the sentence.

Design

Preceding the experiment, participants completed a training session, supposedly to practice the task, during which they produced descriptions of transitive color-coded pictures. The proportion of actives versus passives which was produced during this training session was manipulated between participants. The control group produced active descriptions in 90% of all trials and passive descriptions in 10% of all trials. The experimental group produced active descriptions in 10% of all trials and passive descriptions in 90% of all trials. In this session, pictures depicted one of 10 transitive verbs *(pelt, kiss, make up, punish, transport, scare, embrace, drag, draw, strangle).* For each of these 10 verbs there were 10 pictures. The verbs were different from the 31 transitive verbs encountered later during the syntactic priming experiment.

In the experiment, like in Experiment 1, each trial consisted of a color-coded prime followed by a grayscale target, and there were two types of trials: baseline trials and transitive priming trials (Figure 4). During transitive priming trials we measured the syntactic priming effect in four conditions, resulting from a manipulation of prime structure (active vs. passive), fully crossed with a manipulation of verb repetition (no verb repetition vs. verb repetition between prime and target). With the latter manipulation we investigated the influence of repeating verbs on syntactic priming effects.

Each experimental list contained 48 baseline trials and 24 trials in each of the 4 transitive priming conditions. We generated counterbalanced lists so that each target picture occurred once with a baseline prime, once with an active prime and once with a passive prime across three different experimental lists. Over the whole experiment, half of the items elicited transitives and half of the items elicited other structures. Participants first saw 100 pictures during the training session and then 480 pictures during the actual experiment. Each experimental list was presented to a participant who had a training

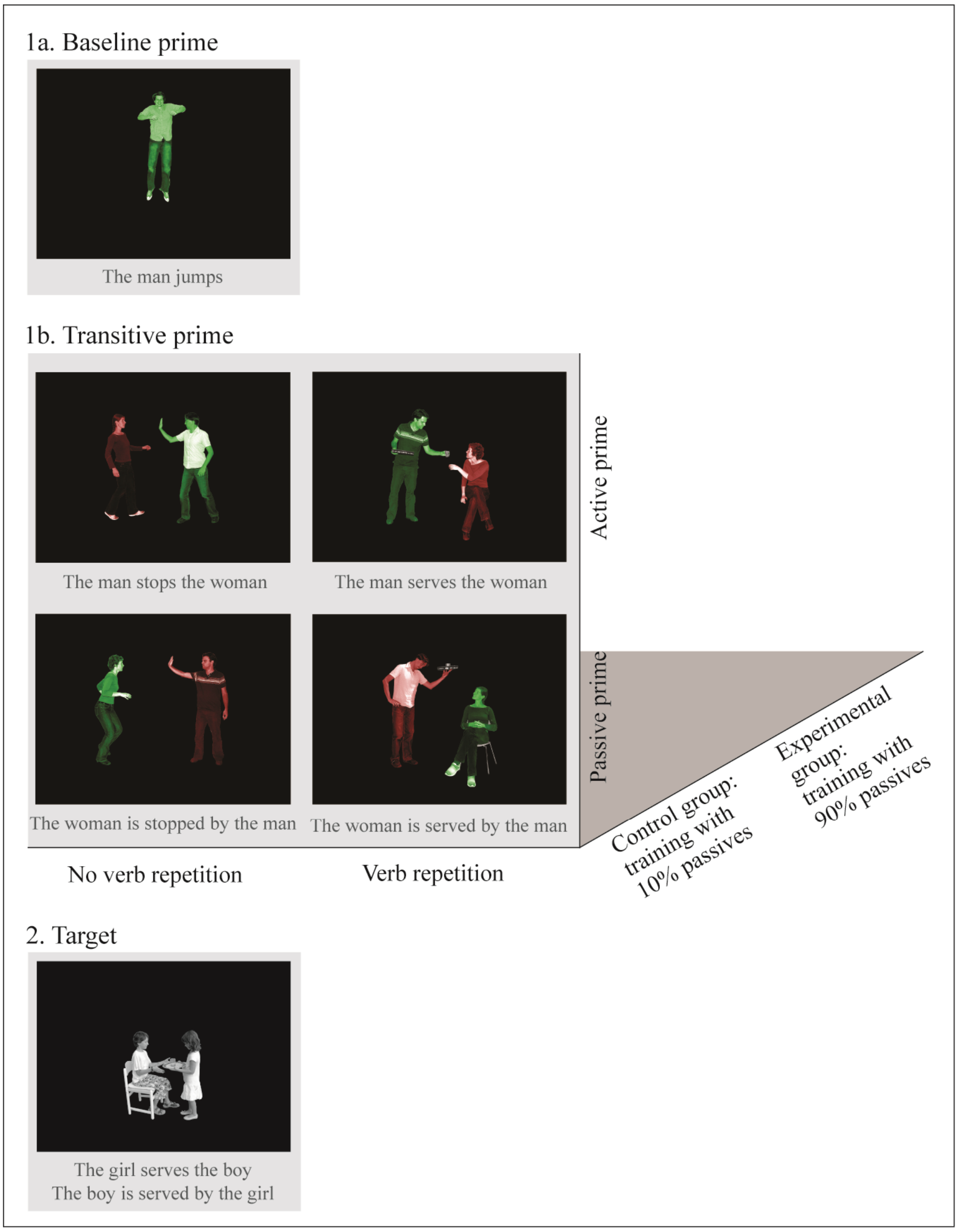

Figure 4. Design Experiment 2. Preceding the experiment, participants completed a training session. The type of training session was manipulated between participants: one group received a training block with 10% passives (the control group) and a second group received a training block with 90% passives (the experimental group). During the actual experiment, each trial consisted of a color-coded prime (1a. or 1b.) and a grayscale target (2.). On baseline trials (1a. followed by 2.) primes were intransitive or locative sentences, so that we could measure the baseline frequency of using active and passive transitives. On transitive priming trials (1b. followed by 2.) we measured the syntactic priming effect for transitive sentences in four conditions. Transitive primes could be active (top row) or passive (bottom row). Furthermore, there could be no verb repetition (left column) or verb repetition (right column) between prime and target. The sentences participants produced responding to the pictures are inserted for clarity.

session with 10% passives and to a participant who had a training session with 90% passives.

Procedure

The training session was portrayed to the participants as a practice session preceding the actual experiment. We told them this practice session would give them a chance to familiarize themselves with the task. The training session lasted 10 minutes. The actual experiment lasted 48 minutes and the procedure followed the one described for Experiment 1 (see also Figure 2).

Results

Response tendencies

We excluded 7.7% of the target responses (669 out of 8640; in group 1: 321 out of 4320 (7.4%) and in group 2: 348 out of out of 4320 (8.1%)) because they were incorrect. We analyzed the responses using mixed-effects logit models in R (Jaeger, 2008; Pinheiro & Bates, 2000). Active targets were coded as 0 and passive targets as 1.

Figure 5a summarizes the proportion of passive responses. The between-group manipulation of structure frequency in the training session produced the effect we expected: in the experimental group the production of passives was boosted compared to the control group. The preference bias changed from 10.5% passives in the baseline condition in the control group to 18.8% passives in the baseline condition in the experimental group.

When we exclude the data from the baseline condition, we can fit a model with the predictors 'Prime structure', 'Verb repetition' and 'Group' (upper part of Table 3). Random subject and item effects were modeled by including a random intercept and slope of 'Prime structure' for subjects and a random intercept for items (this is the maximal random effect structure justified by model comparison). The negative intercept indicates that actives were overall more preferred than passives. Group (p<.008), Prime structure (p<.001) and the interaction between Prime structure and Verb repetition (p<.001) were significant predictors of response tendencies.

To investigate whether prime structure and word repetition change the response tendencies compared to the baseline proportion of passives versus actives in each group, we then analyzed the data of the control group and the experimental group separately, and, analogous to the analyses of Experiment 1, we included the baseline condition in the intercept (middle and bottom part of Table 3). In the control group we modeled random subject and item effects by including a random intercept and random slope of 'Condition' for subjects and a random intercept for items (this is the maximal random effect structure justified by model comparison); in the experimental group we modeled random subject and item effects by including a random intercept and random slope of 'Condition' for subjects as well as for items (this is the maximal random effect structure justified by model comparison).

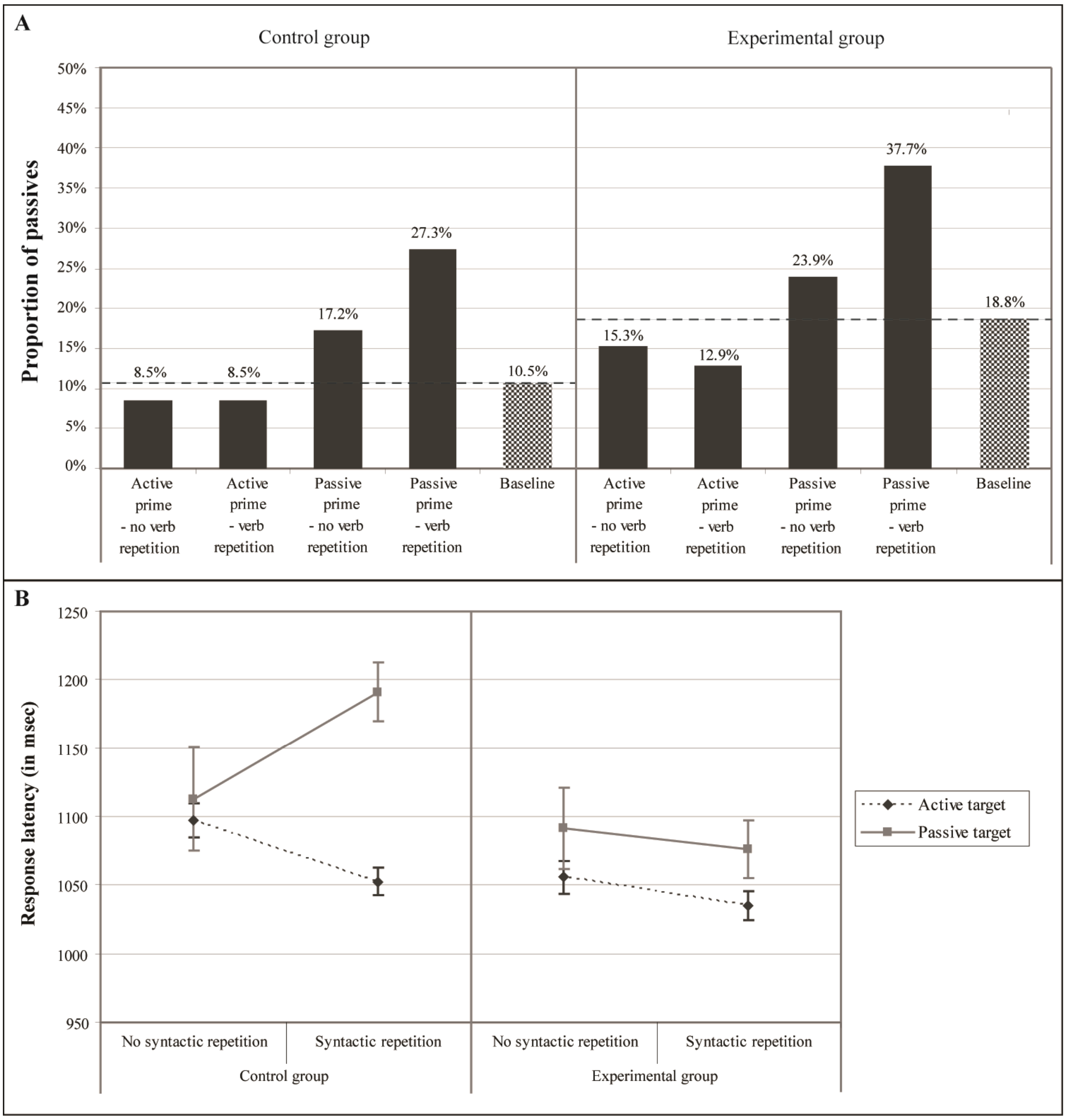

Figure 5. Results Experiment 2 for the control group (left panel) and experimental group (right panel). A) Response tendency results: the proportion of passive transitives is illustrated for each condition, and **B) Response latency results:** mean response latencies and standard errors for each condition.

Table 3. Summary of fixed effects in the mixed logit model for the response tendencies in Experiment 2

Predictor	coefficient	*SE*	*Wald Z*	*p*
For the control and experimental group taken together, excluding the baseline condition (N=5254, log-likelihood=-2141)				
Intercept	-2.87	0.22	-13.24	<.001 ***
Prime	0.82	0.17	4.88	<.001 ***
Verb repetition	-0.16	0.14	-1.18	>.24
Group	0.61	0.23	2.66	<.008 **
Prime by Verb repetition	0.93	0.17	5.53	<.001 ***
For the control group , including the baseline condition in the intercept (N=3972, log-likelihood=-1334)				
Intercept (Baseline)	-2.78	0.23	-12.06	<.001 ***
Active prime - No verb repetition	-0.42	0.21	-1.97	<.049 *
Active prime - Verb repetition	-0.27	0.20	-1.37	>.16
Passive prime - No verb repetition	0.71	0.16	4.56	<.001 ***
Passive prime - Verb repetition	1.44	0.20	7.13	<.001 ***
For the experimental group, including the baseline condition in the intercept (N=3999, log-likelihood= -1822)				
Intercept (Baseline)	-1.79	0.19	-9.60	<.001 ***
Active prime - No verb repetition	-0.42	0.16	-2.63	<.009 **
Active prime - Verb repetition	-1.02	0.21	-4.81	<.001 ***
Passive prime - No verb repetition	0.36	0.14	2.49	<.01 *
Passive prime - Verb repetition	1.07	0.23	4.59	<.001 ***

The negative estimate for the intercept in the control group and in the experimental group indicates that actives were more frequent than passives in both groups in the baseline condition. While in the control group actives were produced arguably more often following an active prime compared to baseline (no verb repetition: $p<.050$, verb repetition: $p>.16$), in the experimental group actives were produced significantly more often following an active prime compared to baseline (no verb repetition: $p<.009$, verb repetition: $p<.001$). Following a passive prime, on the other hand, more passive targets were produced compared to baseline both in the control group (no verb repetition: <.001, verb repetition: <.001) and in the experimental group (no verb repetition: <.01, verb repetition: <.001).

Response latencies pre-experimental training session

In the control group 47 out of 3000 (1.6%) responses during the training session were incorrect. In the experimental group 36 out of 3000 (1.2%) responses were incorrect. Paired samples t-tests on the response latencies of the correct responses revealed that in the control group actives were produced 223.5 ms faster than passives ($t_{29} = -9.642$, $p<.001$) and in the experimental group passives were produced 94.6 ms faster than actives ($t_{29} = 3.240$, $p<.003$).

Response latencies experimental session

We excluded 5.4% of correct responses on transitive priming trials (284 out of 5254; in the control group: 152 out of 2614 (5.8%) and in the experimental group: 132 out of out of 2640 (5.0%)) because they were coded as containing other sounds which triggered the voice key before speech onset or because they were two standard deviations below or above the mean calculated per subject and per condition. Based on participants' target responses we created a post-hoc independent variable 'Syntactic repetition'. Response latencies were analyzed using mixed-effects linear models in R (Baayen et al., 2008; Pinheiro & Bates, 2000).

Figure 5b summarizes the response latency data. We first analyzed the data of the control and experimental group together to investigate the effect of the between-group manipulation of the training session. The fixed effects of the best model fit are summarized in the upper part of Table 4. We modeled between group random subject and item effects by including a random intercept (this is the maximal random effect structure justified by model comparison). In this model estimation, passive targets, no syntactic repetition, no verb repetition and the experimental group are taken as reference, and, importantly, passive targets are included in the intercept. We took passive targets as the reference because we primarily set out to investigate the effect of pre-experimental training on the latencies for passives. For passive targets syntactic repetition slowed down response latencies ($p<.047$), however, and crucially, the interaction between syntactic repetition and group indicates that for passive targets the effect of syntactic repetition is different in the two groups ($p<.012$). While in the control group syntactic repetition increased the latencies for passives, in the experimental group syntactic repetition decreased the latencies for passives. Additionally, the effect of syntactic repetition was different for active and passive targets ($p<.001$) and there was also a three-way interaction between syntactic repetition, target structure, and group ($p<.004$).

Table 4. Summary of fixed effects in the mixed linear model for the response latencies in Experiment 2

Predictor	coefficient	MCMC mean	HPD95 lower	HPD95 upper	*pMCMC*	*Pr(>|t|)*
For the control and experimental group taken together (N=4970, log-likelihood=-34871)						
Intercept (passives)	1079.53	1071.21	-242.22	2295.83	<.08	<.001 ***
Target structure	-5.26	-5.86	-62.22	49.44	>.84	>.85
Syntactic repetition	62.17	61.97	-0.78	120.70	<.047	<.047 *
Group	-24.88	-8.42	-1769.46	1907.81	>.93	>.65
Target structure by Syntactic repetition	-117.15	-116.94	-179.74	-49.99	<.001	<.001 ***
Target structure by Group	-20.55	-20.09	-92.12	50.13	>.58	>.57
Syntactic repetition by Group	-100.23	-99.86	-174.14	-21.02	<.010	<.012 *
Target structure by Syntactic repetition by Group	124.01	123.74	44.24	210.29	<.003	<.004 **
For the control group (N=2462, log-likelihood=-17148)						
Intercept	1074.57	1073.83	1013.07	1131.79	<.001	<.001 ***
Target structure	1.23	2.21	-49.93	56.44	>.94	>.96
Syntactic repetition	-55.30	-55.25	-76.64	-33.49	<.001	<.001 ***
Target structure by Syntactic repetition	119.49	19.23	59.14	180.38	<.001	<.001 ***
For the experimental group (N=2508, log-likelihood= -17723)						
Intercept	1027.27	1026.88	980.40	1075.76	<.001	<.001 ***
Target structure	27.63	27.76	-1.04	55.10	<.051	<.050 *
Syntactic repetition	-33.03	-32.79	-55.22	-10.21	<.005	<.005 ***

Note: Listed are the model estimates and the mean estimate across Markov chain Monte Carlo samples for the coefficients, with the upper and lower 95% highest posterior density intervals and *p*-values based on the posterior distribution and the *t*-distribution (with upper bound degrees of freedom) (Baayen et al., 2008).

Therefore, we investigated the group effect on the latencies for actives next. In order to do this, we estimated the same model but this time we chose active targets as the reference and included active targets in the intercept. The analysis then revealed a main effect of syntactic repetition for actives (β=-54.98, $p<.001$) but no interaction between syntactic repetition and group for this structure (β=23.78, $p>.16$). This means that for active targets syntactic repetition increased the response latencies. In addition, unlike for passive targets, the syntactic repetition effect for active targets was not modulated by the training session (i.e., there was no reliable difference between the control and experimental groups).

Including a predictor for verb repetition (as a main effect: $\chi^2_1 = 0.23$, $p>.63$; or interacting with the other predictors: $\chi^2_8 = 8.17$, $p>.42$) did not improve the model fit of the response latency data of Experiment 2.

To further examine the effect of the between-group manipulation, we analyzed the data of the control group and the experimental group separately. In both groups we modeled random subject and item effects by including a random intercept (this is the maximal random effect structure justified by model comparison). The analysis of the control group (middle part of Table 4) revealed that syntactic repetition decreased response latencies ($p<.001$), but this effect depended on whether the target structure was active or passive ($p<.001$). Therefore, in a similar manner to Experiment 1, a factor with four levels was constructed, making it possible to contrast syntactic repetition to no syntactic repetition for active and passive targets separately. For active targets, response latencies were shorter for syntactic repetition compared to no syntactic repetition (β=-55.30, $p<.001$), while for passive targets, response latencies were longer for syntactic repetition compared to no syntactic repetition (β=64.19, $p<.03$). The analysis of the experimental group (bottom part of Table 4) on the other hand, revealed that syntactic repetition decreased response latencies for both target structures taken together ($p<.005$). Interestingly, in the experimental group, allowing an interaction of syntactic repetition with target structure did not improve model fit ($\chi^2_1 = 0.13$, $p>.72$).

Discussion

In Experiment 2 we aimed to further investigate the role of speakers' pre-existing bias in determining syntactic priming effects of actives versus passives. In the control group of participants, who had a training session maintaining the strong pre-existing bias towards actives, we replicated the syntactic priming effects of Experiment 1. In this group there was a syntactic priming effect for passives in the response tendencies and for actives in the response latencies. In the experimental group however, who had a training session altering the preference bias such that the base rate selection of passives was boosted, we found syntactic priming effects for both structures in the response tendencies as well as the response latencies.

Experiment 2 thus confirms that the preference ratio of two syntactic alternatives is a crucial determinant of syntactic priming, and moreover shows that this bias is dynamic and subject to learning. A relatively short training block which gave participants experience with a high proportion of passive sentences substantially changed their preference bias. The experience during this training block (90% passives and 10% actives) was opposite to their lifelong experience (10% passives and 90% actives). This recent experience added to, but evidently did not replace, their lifelong experience.

With respect to actives, the results of Experiment 2 seem to confirm that a ceiling effect in the baseline frequency may obfuscate response tendency effects for this syntactic alternative. The training session had a reliable impact on the response tendency results for actives. In the control group (where the baseline preference for actives was ~90%), active primes again seemed to slightly affect the response tendencies; the effect just reached significance when there was no verb repetition and did not reach significance when there was verb repetition. However, in the experimental group (where the baseline preference for actives was ~80%) the response tendency effects for actives were much stronger than in the control group, although they were still smaller than for passives. Additionally, Experiment 2 confirmed that there is a reliable and consistent response latency benefit of syntactically repeating the more preferred alternative (i.e., the active).

For passives, the training session had a reliable impact on the response latency effects. In the control group, there was no facilitation of the response latencies when passive structures were repeated - in fact, the results showed increased response latencies. This differs from the finding in Experiment 1 where there was no observable latency effect for syntactically repeated passives. Future experiments need to investigate possible reasons for the difference in results. One possible reason may be the training block that the control group of Experiment 2 had to complete. The ratio between actives and passives in this training block was similar to the one in daily life. But unlike in daily life, these transitive sentences were not mixed with other syntactic structures, thus putting the frequency difference between actives and passives in the spotlight and enhancing the effect. In the experimental group of Experiment 2 there was a facilitation effect in the response latencies for active and passive structures taken together. There was no evidence of an interaction between the effect of syntactic repetition and whether the syntactic structure was active or passive. In this group, the relative frequency of passives was boosted: actives were preferred over passives (~20% passives were produced in the baseline condition) but less so than in the control group (where ~10% passives were produced in the baseline condition).

As a final point, in the present experiment we included a manipulation of verb repetition while the other words in the sentence were not repeated. Although in Experiment 1 we included full word repetition, the results of this manipulation in the two experiments are comparable: verb repetition and, more generally, repetition of content words boosts syntactic priming effects in response tendencies, but not in response latencies. Repetition of the nouns together with repetition of the verb, however, leads to a lexical priming effect in response latencies, but repetition of the verb alone does not.

General discussion

In the present set of experiments we investigated syntactic priming of transitive syntactic structures in Dutch spoken language production using a picture description paradigm. We simultaneously measured response tendencies and response latencies. In Experiment 1, we found that syntactic priming readily affects the response tendencies for passives, while in the response latencies there is only facilitation for syntactically repeated actives. That the difference between actives and passives in these syntactic priming outcomes is related to speaker's preference bias for actives was confirmed by Experiment 2. Following a training session maintaining participants' strong preference bias for actives, we replicated the findings of Experiment 1. However, following a training session altering participants' preference bias such that the base rate of passives is boosted, we found syntactic priming effects for both structures in the response tendencies as well as the response latencies.

For the analyses of the response latencies, we did not manipulate the factor 'Syntactic repetition' but constructed it on the basis of the participants' own responses. Therefore, we can strictly speaking only draw correlational and not causal conclusions regarding the relationship between 'Syntactic repetition' and the response latencies. However in two different studies in which we did manipulate 'Syntactic repetition' as a factor (Menenti et al., 2011; Segaert, Menenti, & Hagoort, 2009), we also found response latency benefits for actives and not passives, indicating that 'Syntactic repetition' causes the response latency effects and not the reverse.

Very few studies have investigated response latency effects of syntactic priming (Corley & Scheepers, 2002; Smith & Wheeldon, 2001; Wheeldon & Smith, 2003) and these did not yet take preference biases into account. Smith and Wheeldon (2001; 2003) found latency effects for noun phrases, structures for which detailed information on preference biases is unknown. Corley and Scheepers (2002) found syntactic priming evidence for English datives in response tendencies as well as response latencies (note however that they only found reliable effects in the verb repetition condition). For datives, preference biases are verb specific (Gries & Wulff, 2005). Corley and Scheepers (2002) used a large set of materials (Pickering & Branigan, 1998) containing verbs with a prepositional object preference as well as verbs with a double dative object preference. Thus, they collapsed the effects of primes with prepositional object preference verbs and double object preference verbs. Teasing these apart may reveal the effects of verb-specific alternation biases on the strength of syntactic priming on response tendencies (Bernolet & Hartsuiker, 2010) and also latencies.

The preference ratio of two syntactic alternatives is a crucial determinant of syntactic priming effects. In response tendencies, not only for active and passive transitives but also for many other structural alternatives, priming with the less preferred structure shows stronger syntactic priming effects (Bernolet & Hartsuiker, 2010; Ferreira, 2003; Hartsuiker, Kolk, & Huiskamp, 1999; Scheepers, 2003). This has been described in the inverse-preference account: learning, displayed as effects of priming on response tendencies, is a function of the degree of preference (Ferreira & Bock, 2006). This is compatible with findings showing that the syntactic system is probabilistic in nature, since the effect of syntactic priming on response tendencies is sensitive to prime surprisal (surprisal is the inverse of probability) (Jaeger & Snider, 2007). In other words, the strength of effects on response tendencies is inversely correlated with the degree of preference for the prime structure (Ferreira & Bock, 2006) or the extent to which the prime structure was expected (Jaeger & Snider, 2007). Both proposals are related to the implicit learning theory (Chang et al., 2006), which specifies that the larger prediction error accompanying less preferred prime structures will lead to larger changes in internal representations and larger effects on response tendencies. In our experiments we found an inverse-preference effect in the response tendencies for transitives. While passive primes reliably and consistently affected the response tendencies, actives primes had a small or absent effect. In Experiment 2, when the preference ratio between actives and passives was less unbalanced and the frequency of passives boosted, there were larger syntactic priming effects in response tendencies for actives than in the control group of Experiment 2 and in Experiment 1.

While error-based implicit learning, inverse-frequency and surprisal accounts can explain the response tendency effects, in their current form these views are not able to explain the response latency results. We have shown in two experiments that there is a convincing facilitatory effect in the response latencies when the *more preferred* syntactic alternative, the active transitive, is repeated. For the less preferred syntactic alternative, the passive transitive, effects on response tendencies are not necessarily accompanied by a response latency benefit. Only when the bias against the less preferred alternative is sufficiently weak, a response latency effect prevails. An important conclusion we can therefore draw is that the response latency effects of syntactic priming do not mirror the response tendency effects.

In sum, we have observed that syntactic priming affects the less frequent, unpreferred construction (i.e. passive) and the more frequent, preferred construction (i.e. active) in different manners: it increases the frequency of the unpreferred alternative and decreases the response latency of the preferred alternative. This dichotomy presents a challenge to the field and to existing theories of syntactic priming: both the implicit learning theory (Chang et al., 2006) and the residual activation theory (Cleland & Pickering, 2003; Pickering & Branigan, 1998) are currently underspecified with regards to response latency effects of syntactic repetition (see introduction). Here, we present a tentative model of our findings - a model partly based on spreading activation and inhibition (competition) between syntactic alternatives. In the next section we describe the model in more detail. We proceed from rather standard assumptions regarding the make-up and functioning of neurons in computational neural network models (Anderson, 1996; McClelland & Rumelhart, 1981). The model could be computationally implemented in future work to test its performance.

A competition model of syntactic priming

We assume that grammatical encoding of a transitive event proceeds in two sequential stages: (1) *a selection stage*, during which one of the alternative syntactic constructions is selected, and (2) *a planning stage*, during which production of the selected construction is prepared. We now describe in more detail the processes that take place in each stage.

Selection stage. Whether the conceptual representation of a perceived event that includes a transitive action is grammatically encoded in Active or Passive Voice, depends on, among other things, the current levels of activation of nodes (or neural assemblies) representing the Active Voice and the Passive Voice constructions. The activation level of the nodes can vary between 0 and 1. We assume that a node's "resting level" (or "base level") of activation is positively correlated with its frequency of occurrence, in particular that the Active Voice node has a higher resting level than the Passive Voice node. Noise causes random fluctuation around the current average activation level even in the absence of other causal factors. (In an unprimed or resting situation, there are three influences enabling the Passive Voice to be selected occasionally as response choice despite its generally lower resting level activation: (1) random fluctuations due to noise, (2) feedforward activation from e.g. the semantic/conceptual representation of a picture during an experimental manipulation, and (3) feedback activation due to pragmatic factors (e.g., the patient of the transitive action being in the focus of attention). Nodes transmit activation and inhibition (=negative activation) to neighboring nodes in the network. There are inhibitory links between the two competing structural alternatives (with invariant stable weights, which we assume to be identical in either direction). The amount of inhibition transmitted to a competitor node is a positive function of the current level of activation. Activation coming in from neighboring nodes is added to the current activation of the node, and incoming inhibition is subtracted from the current activation level. Due to decay of activation, the current activation level decreases in each cycle by a small percentage.

The activation level of a node is updated during every processing cycle in the following way: the activation at the onset of cycle $t + 1$ equals the activation at cycle t multiplied by the decay factor (e.g. .95), plus the activation coming in from neighboring nodes during cycle t, minus the inhibition from the competitor node during cycle t. A "squashing function" serves to keep the resulting activation between the upper and lower bounds of 1 and 0, respectively. Both nodes have two thresholds: a relatively low "excitation threshold" (e.g. at activation a=.3), and a relatively high "selection threshold" (e.g. a=.9). At activation levels below the excitation threshold, the nodes are "dormant"; that is, they do not emit any activation or inhibition. The resting levels of both competitor nodes are below the excitation threshold. For simplicity, we assume that the Active Voice and Passive Voice nodes have identical excitation thresholds, and identical selection thresholds. Reaching the selection threshold means that the node "fires" and that the corresponding construction (Active Voice or Passive Voice) is selected. After firing, the activation level drops gradually due to decay, finally returning to the dormant state and reaching the resting level of activation. The activation between the moments of firing and reaching the resting level is usually called "residual activation."

The intention to describe a transitive event causes activation be to sent to both the Active and the Passive Voice nodes. This activation transmission continues until one of the competitor nodes reaches the selection threshold and fires. The time it takes to reach a selection threshold is determined by the time needed to solve the competition between the Active Voice node and the Passive Voice node. This time is negatively correlated with the difference in activation levels between the two competitors at the moment the competition starts: the higher the current activation of a node, the more inhibition it transmits to the competitor; and the lower the latter's activation, the less inhibition it can retort. Hence, the time needed to determine the winner of the competition *de*creases with an *in*creasing difference in activation levels between competitors, other things being equal. In other words, when priming increases the difference in activation levels between competitors (compared to the difference in base-level activation of the competitors), priming decreases the competition time. When priming decreases the difference in activation levels between competitors (compared to the difference in base-level activation of the competitors), it increases the competition time.

Planning stage. Once either the Active Voice or the Passive Voice is selected, production of the selected alternative is planned. We assume, in line with Levelt & Kelter (1982), that priming reduces the planning time as an effect of practice.

Effects of syntactic priming. The model sketched above implies that the choice of a syntactic construction is determined exclusively during the selection stage. The response latency, on the other hand, depends on the course of events in both the selection stage and the planning stage: the durations of these stages contribute to the response latency as additive effects.

In reaction to an Active Voice prime (the more frequent construction), the following scenario unfolds. Since the relative frequency of active sentences is close to ceiling already prior to priming, the residual activation due to the priming manipulation cannot increase the selection frequency of the active construction to a large extent. Hence, the response tendency effect is very small or absent. The selection time may be slightly shorter (compared to the unprimed situation) since residual activation on the

Active Voice node has increased the gap between the activation levels of the competitors. The planning stage, too, can proceed faster due to the practice effect. The effect on the selection time and the effect on the planning time are additive and result in faster response latencies.

Priming with a passive sentence (the infrequent alternative), temporarily increases the activation level of the Passive Voice node due to residual activation, thereby narrowing the gap with the competitor's activation level, or even reversing the momentary balance of power. As a consequence, the frequency of passives can increase. Crucially, the average time needed for the Passive Voice node to win the competition increases as well due to the reduced gap between activation levels of the competitors. The ensuing lengthening of the selection stage is not visible in the overall response latency because, during the planning stage, passives profit from the practice effect. The shortened planning time compensates fully (experiment 1) or partly (control group experiment 2) for the lengthened selection time.

Lexical influences on syntactic priming effects. On the assumption of a lexicalized grammar (e.g. Vosse & Kempen, 2000), we hypothesize an activation-and-competition network with an Active Voice node and a Passive Voice node for every transitive verb. The Active Voice node of a particular verb inhibits the Passive Voice node of this particular verb but also activates the Active Voice nodes of other verbs (the same applies to Passive Voice nodes). The lexical boost in the response tendency results for passives could then be explained as follows: priming with a passive sentence temporarily increases the activation level of the Passive Voice node for the prime verb (as described) and also, but to a smaller extent, increases the activation level of the Passive Voice node for other verbs. For syntactic priming of actives, due to the ceiling effect in the base level activation, the selection stage can only be affected by syntactic priming and by word repetition to a small extent. The practice effect in the planning stage is unlikely to be influenced by verb repetition since for actives it is reasonable to assume that no more than only the first noun phrase is planned (Allum & Wheeldon, 2007). Possibly because any lexical boost in the selection stage is very small for actives and because a lexical boost is absent in the planning stage, the added effect of the two may not result in an apparent lexical boost of the response latency effects for actives.

The implications for existing theories of syntactic priming

While our specific interpretation of these results in terms of a competition model is up for discussion, the results have important implications for existing theories on the mechanism behind syntactic priming. To be able to account for our findings, a theory of syntactic processing would have to comprise the following features: firstly, the syntactic priming mechanism would have to be sensitive to the preference bias of two syntactic alternatives. Secondly, the mechanism would have to be dynamic, such that the preference bias can change over time due to exposure to these syntactic alternatives. Thirdly, the mechanism would have to be able to explain that effects on response tendencies are larger for the less frequent/preferred primes (e.g. passives) than for more frequent/preferred primes (e.g. actives). So far, considering these first three features, the error-based implicit learning, inverse-frequency and surprisal accounts are good candidates. However, a fourth feature that the mechanism would have to be able to account for, is that syntactic priming effects manifest themselves differently in the response tendencies and the response latencies. In response latencies the effects are larger for the *more* frequent/preferred primes (e.g. actives). One possible suggestion is that (existing) theories could incorporate a competition mechanism as described in the previous section; other suggestions could be proposed and tested in future experiments. The fifth feature which our current findings shed light on is that response tendency effects are boosted by lexical overlap between the prime and target sentence, while the response latency benefit is not influenced by lexical overlap. A final piece of this puzzle is the time course of syntactic priming effects. Our experiments did not include a timing manipulation, but, while response tendency effects are found to be relatively long-lived, Wheeldon and Smith (2003) have observed that response latency effects are short-lived (Ferreira & Bock, 2006; Pickering & Ferreira, 2008; Reitter, Keller, & Moore, 2011). To further shape the theories of syntactic processing, we believe that future studies should not focus exclusively on effects in response tendencies but also investigate effects in response latencies.

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Chapter 3

The influence of verb preferences on the processing of syntactic structures

Speakers sometimes repeat syntactic structures across sentences, a phenomenon called syntactic priming. We investigated the influence of verb-specific syntactic preferences on syntactic priming effects in response tendencies and response latencies for German ditransitives. In the response tendencies we found *inverse (negative)* effects of preference: there were stronger syntactic priming effects for primes in the *less* preferred structure, given the syntactic preference of the prime verb. In the response latencies we found *positive* effects of preference: there were stronger syntactic priming effects for primes in the *more* preferred structure, given the syntactic preference of the prime verb. This supports the idea that syntactic processing is lexically guided.

Adapted from: Segaert, K., Weber, K., Cladder-Micus, M., Hagoort, P. (submitted). The influence of verb preferences on the processing of syntactic structures.

Introduction

Both *'liefern' [to deliver]* and *'verkaufen' [to sell]* are ditransitive German verbs that can be used in the double object or alternatively the prepositional object dative construction. However, for *'liefern',* the double object dative construction *(e.g. 'Der Junge liefert dem Mädchen ein Paket' [The boy delivers the girl a package])* is preferred, while for *'verkaufen'*, the prepositional object dative construction *(e.g. 'Die Frau verkauft die Blumen an den Mann' [The woman sells flowers to the man])* is preferred (Schulte im Walde, 2003).

Lexicalist grammar formalisms (Jackendoff, 2002) propose that syntactic processing is strongly lexically guided. Confirming this idea, verb-specific syntactic preferences have been found to affect syntactic processing (Melinger & Dobel, 2005; Trueswell & Kim, 1998; Trueswell, Tanenhaus, & Kello, 1993). Furthermore, while speakers often choose to repeat syntactic structures across sentences (syntactic or structural priming: Bock, 1986), not all sentences influence syntactic production choices to the same extent. The strength of syntactic priming effects on production choices is inversely related to the degree to which the structure of a prime sentence was preferred (Ferreira & Bock, 2006), even when the syntactic preference is determined by the main verb (Bernolet & Hartsuiker, 2010; Jaeger & Snider, 2007). This has been termed the *inverse preference effect* (Ferreira & Bock, 2006). In other words, a sentence in the double object dative structure containing the verb *'verkaufen'* (with prepositional object dative preference) may influence speakers more to reuse this particular structure than a sentence in the double object dative structure containing the verb *'liefern'* (with double object dative preference). The implicit learning theory of syntactic priming can account for findings demonstrating the inverse effect of preference (Chang, Dell, & Bock, 2006; Chang, Dell, Bock, & Griffin, 2000). This error-based learning account proposes that the larger prediction error accompanying less preferred prime structures (given the preference of the verb) will lead to larger changes in internal representations and larger effects on syntactic response choices. Lexically-driven syntactic priming effects can be accounted for by the residual activation theory (Pickering & Branigan, 1998).

The strength of syntactic priming effects on response tendencies is thus inversely related to the degree of preference for the prime structure, given the syntactic preference of the verb. But how about syntactic priming effects on response latencies? Are these also affected by verb-specific syntactic preferences?

Several studies have now demonstrated that syntactic priming results in faster sentence production latencies (Corley & Scheepers, 2002; Smith & Wheeldon, 2001; Wheeldon & Smith, 2003). Segaert et al. (2011) found that priming of the less preferred syntactic alternative (passives) mainly affects the response tendencies, while priming of the more preferred syntactic alternative (actives) mainly affects the response latencies. We proposed a competition model of syntactic priming, explaining effects on response tendencies as well as response latencies.

In this competition model, syntactic encoding consists of two sequential stages. In the first stage, one syntactic alternative is selected. In the second stage, production is planned. The choice of a syntactic construction is determined exclusively during the selection stage. The selection time in stage one and the planning time in stage two contribute to the response latency as additive effects. The result of the selection stage is largely determined by the base-level activation of two competing nodes representing the two alternative syntactic constructions. The base-level activation of a node is positively correlated with the frequency of occurrence of the syntactic alternative it represents. In a lexicalized grammar, nodes represent syntactic alternatives per verb, allowing verb-specific preferences to determine syntactic encoding. A crucial aspect of the competition model is that inhibition (negative activation) is transmitted between competing alternatives; the amount of inhibition transmitted is a positive function of the current activation level. The time it takes to reach a selection threshold (the selection time) is determined by the time needed to solve competition between the nodes. This time *de*creases with an *in*creasing difference in activation levels between competitors at the moment competition starts: the higher the current activation of a node, the more inhibition it transmits to the competitor; the lower the latter's activation, the less inhibition it can retort. We assume that competitor nodes have identical selection thresholds. When activation reaches the selection threshold, it means that the node "fires" and that the corresponding syntactic construction is selected. After a node fires, the activation level drops gradually due to decay (it decreases by a small percentage in each cycle until it eventually goes dormant). Thus, priming temporarily increases the activation level of the node representing the primed structure due to residual activation, which in turn may influence the response tendencies.

The competition model assumes an *inverse (negative)* effect of preference on syntactic priming effects in response tendencies. When a more unpreferred structure is primed (given the preference of the verb), the chance that the activation level of the corresponding node has not yet returned to the base-level activation during the target response is higher (compared to when a less unpreferred structure is primed). When a more unpreferred structure is primed, the response tendencies are thus more likely to be affected. The competition model assumes a *positive* effect of preference on syntactic priming effects in the response latencies. Effects on response latencies are the result of the additive effects on the selection time and the planning time. For a more preferred structure (given the preference of the verb), priming increases the difference in activation levels between competitors more strongly, and thus priming decreases the competition time more strongly (than for a less preferred structure). In the planning stage we assume, in line with Levelt & Kelter (1982), that priming reduces the planning time as an effect of practice.

In the present study we investigated the effect of verb-specific syntactic preferences on syntactic priming of ditransitive sentences in German spoken language production. Syntactic preferences for ditransitive verbs are verb-specific. In German, verb-specific preferences have a wide-ranging distribution. We used a picture-description paradigm and simultaneously measured response tendencies and response latencies. We manipulated the degree to which the syntactic structure of prime sentences was preferred, given the preference of the verb: prime sentences either had a double object or prepositional object dative syntactic structure, containing a verb with a preference for either the double object or the prepositional object dative. In addition to *inverse (negative)* syntactic priming effects of preference on response tendencies, we expected to find *positive* effects of preference on response latencies.

Method and materials

Participants

60 native German speakers gave informed consent prior to the experiment and were compensated for their participation. We excluded 7 participants who indicated in a

Table 1. The preference for the double object dative structure according to three different measures (on a scale between 0 and 1) for each verb separately.

Verb	Schulte im Walde, 2003	Pretest results "How normal do you consider this sentence?"	Pretest results "Do you like this sentence?"	Preference for double object or prepositional object datives
leihen	0.98	0.64	0.56	double object
verabreichen	0.74	0.68	0.61	double object
reichen	0.68	0.69	0.65	double object
liefern	0.66	0.55	0.60	double object
zeigen	0.63	0.75	0.68	double object
servieren	0.60	0.72	0.62	double object
vorlesen	0.59	0.52	0.52	double object
machen	0.55	0.55	0.55	double object
suchen	0.45	0.36	0.40	prepositional object
verkaufen	0.44	0.45	0.49	prepositional object
nähen	0.43*	0.44	0.42	prepositional object
reservieren	0.41	0.43	0.46	prepositional object
bauen	0.34	0.46	0.54	prepositional object
schlachten	0.27	0.38	0.44	prepositional object
deuten	0.26	0.42	0.47	prepositional object
bewachen	0.13	0.39	0.40	prepositional object

Note: The first measure is based on data of Schulte im Walde (2003, data obtained through personal communication) on the use of a variety of subcategorisation frames for all German verbs in a 35 million word newspaper corpus. For a subset of these verbs we pulled together the subcategorisation frames indicative of a double object versus a prepositional dative (a similar approach was taken by Gries and Wulff (2005) for a smaller subset of verbs). Additionally, we collected ratings through an internet-based questionnaire in which 42 native German speakers participated. A randomized list of 36 verbs in the double object versus prepositional dative structure was rated on a 7-point scale with respect to how normal the participants judged the sentence to be *('Wie normal findest du diesen Satz?')* and how much they liked the sentence *('Magst du diesen Satz?')*. For this experiment we used the 16 verbs which were depictable and converged on the three measures in terms of which structural alternative was categorically preferred.

*Because nähen was not included in the corpus of Schulte im Walde (2003), we used the average of the values obtained in our pretest questionnaire post-experimental questionnaire to have been raised with a German dialect, thus including 53 participants (20 male/33 female, mean age of 22 years with SD 2.2).

Materials

Our stimulus pictures depicted 16 ditransitive events such as *lending, selling, showing*. For each ditransitive verb, table 1 lists the preference for the double object versus prepositional dative structure based on three different measures. In the stimulus pictures a ditransitive event was depicted with an animate subject, one animate and one inanimate object of the action, for the elicitation of ditransitive sentences. Each event-object pair was enacted with two inanimate objects (for a list of the inanimate objects paired with each event: see Appendix 2.2) and three couples of actors (2 x man/woman; 1 x boy/girl). Each of these scenes was enacted once with the male actor as subject and once with the female actor as subject. Each picture also had a version with the subject on the left and with the subject on the right. Each ditransitive picture had three versions: one grayscale version and two color-coded versions with a green, an orange and a red object or actor (which elicited either a double object or prepositional object dative - see task description). Filler pictures elicited intransitive sentences, depicting events such as *running, singing, bowing* with one actor (in grayscale, green, orange or red).

Task and design

Participants were instructed to describe pictures with one sentence, naming first the green, then the orange and then the red element in the picture. The colors of a traffic light served as a mnemonic to remember the order. If the elements in the picture were not depicted in color then participants did not have to pay attention to the order of mentioning and could therefore freely choose to produce either a double object dative or a prepositional dative.

There were two types of trials: baseline trials and dative priming trials. On baseline trials, primes were intransitive sentences so that we could measure the baseline frequency of producing double object versus prepositional datives on subsequent targets. On dative priming trials we measured the syntactic priming effect in eight conditions, resulting from a manipulation of prime structure (double object versus prepositional datives), fully crossed with the syntactic preference of the prime verb (double object versus prepositional datives) fully crossed with the syntactic preference of the target verb (double object versus prepositional datives). See Figure 1.

Intransitive sentences *('The man jumps')* served as fillers, such that over the whole experimental list 40% of the items elicited intransitives sentences. In total, each experimental list contained 80 baseline trials and 20 trials in each of the 8 dative priming conditions. We generated counterbalanced lists so that each dative target picture occurred once with a baseline prime, once with a double object dative prime and once with a prepositional dative prime across three different experimental lists.

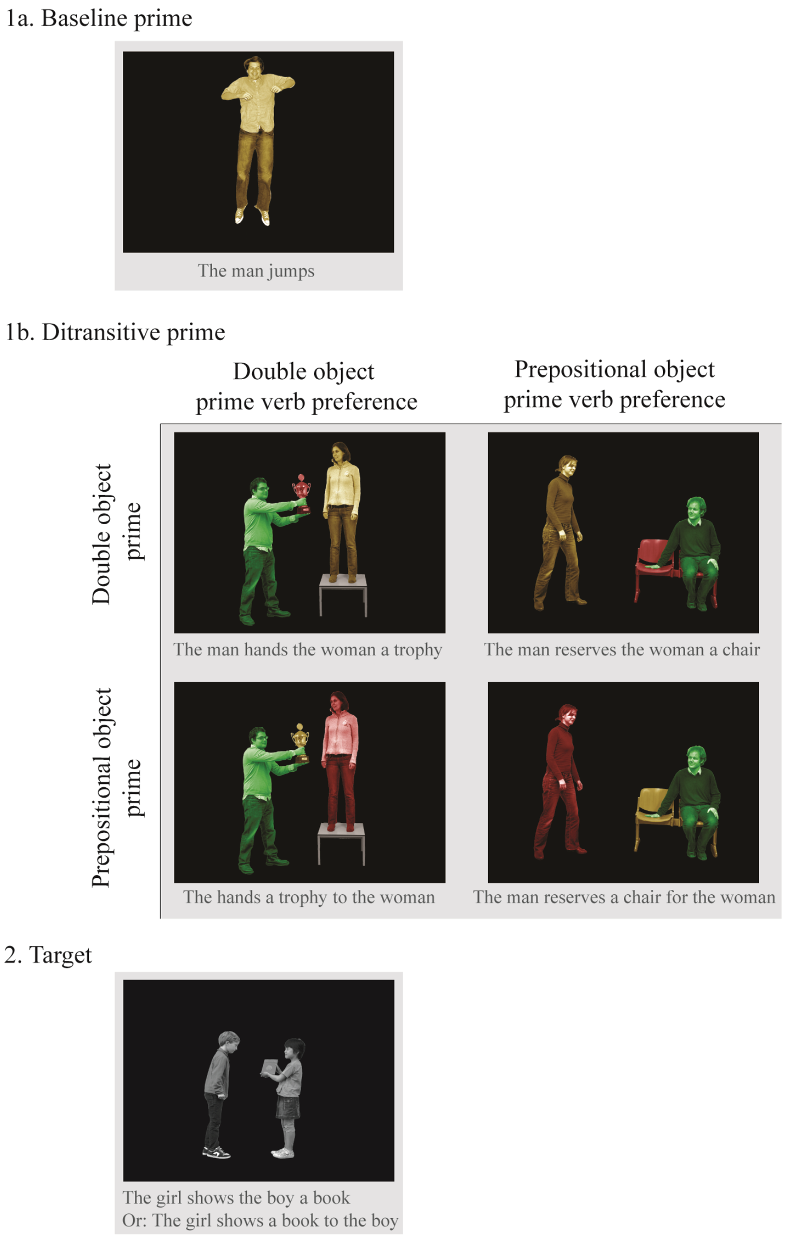

Figure 1. Design. Each trial consisted of a prime followed by a target. Primes were pictures in which elements were color-coded for the order of precedence in the sentence, allowing us to manipulate the syntactic structure participants would produce. A grayscale target eliciting a ditransitive sentence immediately followed the prime. We measured which structure participants used to describe target pictures: the double object versus prepositional object dative (e.g. *Das Mädchen zeigt dem Jungen das Buch,* versus *Das Mädchen zeigt das Buch an den Jungen*; in this case the target verb *zeigen* has a preference for the double object structure). Additionally, we measured participants' response latencies on the target pictures. On baseline trials, primes were intransitives, so that we could measure the baseline frequency of using double object versus prepositional datives. On dative priming trials, we measured the syntactic priming effects of datives in eight conditions. Dative primes were produced in the double object or prepositional dative structure, and the prime verb had a preference for the double object or for the prepositional object dative. Additionally (but not depicted in the figure), the target verb had a preference for the double object or for the prepositional object dative. The English translation of the sentences participants produced is inserted for clarity.

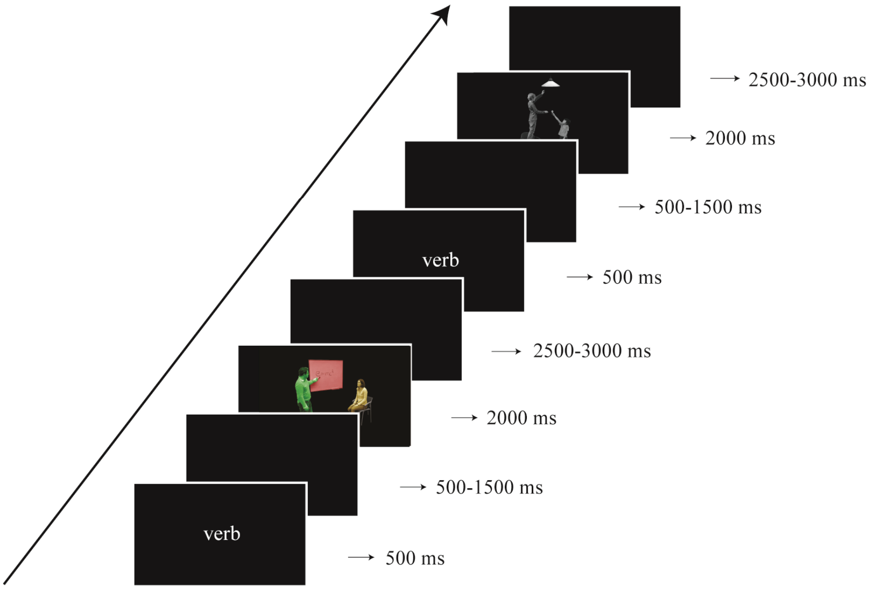

Figure 2. Procedure. Each trial consisted of the following events: a verb was presented in its infinitive form and after a jittered interval the prime picture was presented. After a next jittered interval a verb was again presented, followed by the next jittered interval and a target picture. After another jittered interval the next trial started.

Procedure

Participants were first presented with pictures of the inanimate objects (which would be depicted during the experiment) together with their names, and then received ten practice trials. The actual experiment lasted 70 minutes; figure 2 illustrates the sequence of events on each trial. Participants' responses were recorded and a voice key measured response latencies from picture presentation. We used the following criteria to determine whether target responses were included for analysis: if 1) a correct ditransitive response (either a double object or prepositional dative) was given as the target sentence, 2) the correct structure was used on the prime trial and 3) both actors and the inanimate object were named accurately and the verb was used correctly on both prime and target trial. Debriefing showed that participants were unaware of the underlying experimental manipulation.

Results

Response tendencies

We excluded 30% (3818 out of 12720) of the responses because they were incorrect. We analyzed the responses using mixed-effects logit models (Jaeger, 2008; Pinheiro & Bates, 2000) in R (R Development Core Team, 2009). We fit a model with the predictors 'Prime structure', 'Prime verb preference', 'Target verb preference'[1]. Target responses were coded as 0 for double object datives and 1 for prepositional object datives. We included a random intercept and random slopes of 'Prime structure' and 'Target verb preference' for subjects and a random intercept for items (this is the maximal random effect structure justified by model comparison).

Figure 3 summarizes the relative proportion of prepositional object dative responses. The fixed effects of the best model fit are summarized in Table 2. The negative estimate for the intercept indicates that in the baseline condition double object datives were more frequent than prepositional object datives. There was no main effect of double object dative primes on the response tendencies compared to the baseline ($p>.43$), but there was an effect of prepositional object dative primes compared to the baseline ($p<.001$).

Next we turn to an investigation of the effect of verb preferences. The strength of prepositional object dative priming did not depend on the prime verb preference ($p >.89$), but the strength of double object dative priming did ($p<.05$): double object dative primes for which this structure was unpreferred had a stronger effect on response tendencies than double object dative primes for which this structure was preferred. Target verb preference also affected the response tendencies ($p<.001$). Allowing target verb preference to interact with the effect of prime structure did not improve the model fit ($\chi^2_2 = 1.55$, $p>.46$).

We also estimated models including continuous information about verb preference (as listed in Table 1) instead of categorical information. This did not yield significant results: prime verb preference as measured by Schulte im Walde (2003) did not interact with the effect of the double object prime ($\beta=0.46$, $p>.23$) or the prepositional object prime ($\beta=0.11$, $p>.77$); prime verb preference as measured by our pretest data ("How normal do you consider this sentence") did not interact with the effect of the double object prime ($\beta=0.91$, $p>.13$) or the prepositional object prime ($\beta=0.16$, $p>.79$); prime verb preference as measured by our pretest data ("Do you like this sentence") did not interact with the effect of the double object prime ($\beta=1.45$, $p>.11$) or the prepositional object prime ($\beta=0.34$, $p>.70$).

Response latencies

We excluded 5.4% of correct responses on transitive priming trials (290 out of 5415) because they contained sounds triggering the voice key before speech onset or because they were two standard deviations below or above the mean calculated per subject and per condition. We created a post-hoc variable 'Syntactic repetition' based on the

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[1] Possible prime structures are intransitive baseline primes, double object dative primes and prepositional object dative primes. In order to compute the interaction between the effect of double object and prepositional dative priming (versus baseline) and the effect of prime verb preference, we needed to insert random prime verb preference data for the intransitive primes in the baseline condition. Since each target occurred in three counterbalanced lists (once with a baseline prime, once with a dative prime in double object prime structure and once with a dative prime in prepositional object prime structure – see procedure), we assigned each item in the baseline condition the same prime verb preference value as the corresponding dative prime verb (like Bernolet and Hartsuiker (2010)).

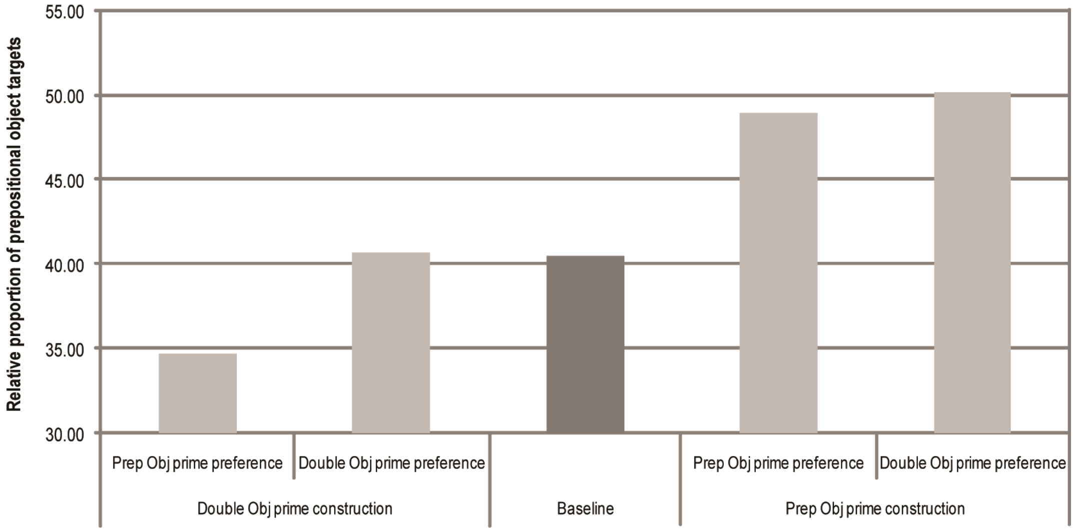

Figure 3. Response tendency results. The relative proportion of prepositional object datives is illustrated for each condition. The strength of prepositional object dative priming does not seem to depend on the preference of the prime verb, but the strength of double object dative priming is shown to depend on the prime verb preference.

Table 2. Summary of fixed effects in the mixed logit model for the response tendencies.

Predictor	coefficient	*SE*	*Wald Z*	*p*	
Intercept (Baseline)	-2.50	(0.27)	-9.09	<.001	***
Prime structure: double obj.	0.09	(0.11)	0.78	>.43	
Prime structure: prep. obj.	0.56	(0.14)	4.07	<.001	***
Prime verb preference	0.09	(0.10)	0.89	>.38	
Target verb preference	3.60	(0.30)	12.07	<.001	***
Prime structure: double obj by Prime verb preference	-0.31	(0.16)	-1.96	<.05	*
Prime structure: prep. obj. by Prime verb preference	-0.02	(0.15)	-0.13	>.89	

Note: N=8902, log-likelihood=-3546

relationship between prime structure and the structure of the participant's target response. Response latencies were analyzed using mixed-effects linear models (Baayen et al., 2008; Pinheiro & Bates, 2000) in R. We fit a model with the predictors 'Target structure', 'Prime verb preference', 'Target verb preference' and 'Syntactic repetition'. As reference conditions we used: double object target structure, no syntactic repetition and double object prime verb preference. We modeled random subject and item effects by including a random intercept (this is the maximal random effect structure justified by model comparison).

Figure 4 summarizes the response latency data. The fixed effects of the best model fit for these data are summarized in Table 3. There was a main effect of syntactic repetition (p>.001) but there was also a two-way interaction between syntactic repetition and target structure (p<.001) and a two-way interaction between syntactic repetition and prime verb preference (p<.005). This indicates that syntactic repetition speeds up response latencies, but more strongly for double object than prepositional object targets and more strongly following double object than prepositional preferred prime verbs. Furthermore, there was a three-way interaction between syntactic repetition, target structure and prime verb preference (p<.001), indicating that the syntactic repetition effect on response latencies depends on the relationship between the prime verb preference and the target structure (see figure 4A). Including target verb preference as predictor in the model did not improve the model fit ($\chi^2_1 = 1.49$, p>.22).

We also estimated models including continuous information about verb preference and these models yielded the same results as models including categorical information. The following three models were estimated with a random intercept for subjects and items and a random slope of 'Target structure' for subjects. In all three models, there was a three-way interaction between syntactic repetition, target structure and prime verb preference. This three-way interaction was significant when we used the prime verb preference information as measured by Schulte im Walde (2003) (β=305.87, p<.001), when we used the prime verb preference information as measured by our pretest data with the question "How normal do you consider this sentence" (β=443.25, p<.002) and when we used the prime verb preference information as measured by our pretest data with the question "Do you like this sentence" (β=597.13, p<.005). Figure 4B illustrates that the syntactic repetition effect (no syntactic repetition minus syntactic repetition) in the response latencies is positively correlated with the degree to which the structure was preferred for the prime verb.

Discussion

In the present study we investigated the effect of verb-specific syntactic preferences on syntactic priming of ditransitive sentences in German spoken language production. We used a picture-description paradigm and simultaneously measured response tendencies and response latencies. Firstly, the response tendencies showed overall and verb-specific *inverse (negative)* effects of preference. There was a stronger effect of primes in the prepositional object dative structure (which is overall less preferred in German (Loebell & Bock, 2003)) than of primes in the double object dative structure. Furthermore, the strength of double object dative priming in the response tendencies was sensitive to the

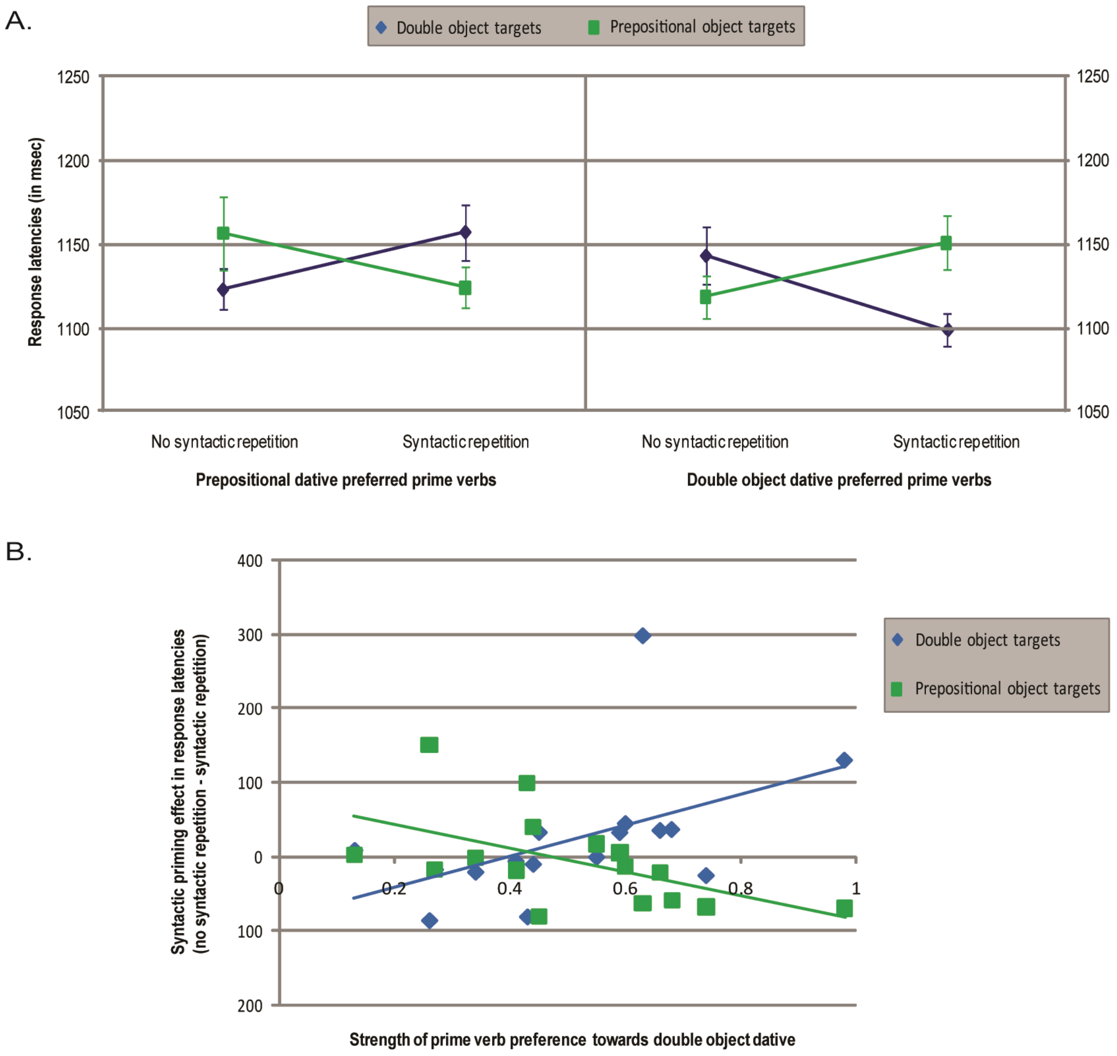

Figure 4. Response latency results. A) Depicted are the mean response latencies and standard errors for double object and prepositional object targets, separated for prime verbs with a double object preference (left panel) and for prime verbs with a prepositional object preference (right panel). Response latencies are facilitated for syntactically repeated compared to not-repeated double object target structures if the prime verb had a double object preference. Response latencies are also facilitated for syntactically repeated compared to not-repeated prepositional object target structures if the prime verb had a prepositional object preference. **B)** Depicted is the response latency priming effect (no syntactic repetition minus syntactic repetition) for double object and prepositional object targets in function of the strength of the prime verb preference towards the double object dative structure as measured by Schulte im Walde (2003). The syntactic repetition effect in response latencies for double object targets is stronger for prime verbs with a stronger preference towards the double object structure. Furthermore, the syntactic repetition effect in response latencies for prepositional object targets is stronger for prime verbs with a stonger preference towards the prepositional object structure.

Table 3. Summary of fixed effects in the mixed linear model for the response latencies.

Predictor	coeffi-cient	*SE*	df	t-value	*Pr(>|t|)*
Intercept	1155.41	27.01	3956	42.77	<.001 ***
Target structure	-31.72	19.99	897	-1.59	>.11
Syntactic repetition	-60.38	16.82	897	-3.59	<.001 ***
Prime verb preference	-21.00	18.23	897	-1.15	.>25
Syntactic repetition by Target structure	92.57	24.78	897	3.73	<.001 ***
Target structure by Prime verb preference	40.00	27.18	897	1.47	>.14
Syntactic repetition by Prime verb preference	65.91	23.56	897	2.80	<.005 **
Syntactic repetition by Target structure by Prime verb preference	-116.45	36.07	897	-3.23	<.001 ***

Note: N=4913, log-likelihood=-34910. Listed are *p*-values based on the *t*-distribution (with upper bound degrees of freedom). There are good arguments in favor of calculating the mean estimate across Markov chain Monte Carlo samples for the coefficients and the *p*-values based on the posterior distribution instead (Baayen, Davidson, & Bates, 2008), but MCMC sampling has not yet been implemented for models with random slopes.

syntactic preference of the verb used in the prime sentence. Secondly, the response latencies showed overall and verb-specific *positive* effects of preference. There was a stronger speed-up for syntactically repeated double object datives (which are overall more preferred in German) than for syntactically repeated prepositional object datives. Furthermore, the strength of double object dative as well as prepositional object dative priming in the response latencies was positively correlated with the degree to which the syntactic structure was preferred for the verb used in the prime sentence.

Inverse effects of preference in the response tendencies and positive effects of preference in the response latencies provide support for a competition model of syntactic priming (Segaert et al., 2011). Even syntactic preferences which are verb-specific determine syntactic processing, supporting the lexicalist nature of the competition model.

The verb-specific inverse preference effect on the response tendencies in the present experiment was less strong than the verb-specific effect in Bernolet and Hartsuiker (2010). We found a categorical but no continuous effect, while Bernolet and Hartsuiker (2010) found both. The reason for this could be the different distribution of verb-specific syntactic preferences of Dutch ditransitives (Bernolet & Hartsuiker, 2010) versus German ditransitives (present experiment). In Dutch, most ditransitive verbs have a preference for the prepositional object dative and this is reflected in the materials of Bernolet and Hartsuiker (2010) (except for two prime verbs, prime and target verbs had a preference for the prepositional object dative). So within their experiment, there was a relatively uniform representation of verb-specific preferences and this kept the overall preference in place for prepositional object datives in the Dutch language (76% of datives in the baseline are prepositional object datives). In German, there is a more diverse representation of verb-specific syntactic preferences and this is reflected in the materials of our experiment (both for prime and target verbs, there were as many verbs with a preference for the double object dative, as there were with a preference for the prepositional object dative). In a situation like this, with a large range of variation in the verb-specific preferences and a relatively weak overall bias (41% of datives in the baseline are prepositional object datives), the influence of verb-specific preferences on syntactic priming may be less strong.

Comparison between languages indicates that verb-specific syntactic preferences are not an inherent aspect of the semantics of a verb. For instance, the verb *'to show'* in Dutch *['tonen']* has a preference for the prepositional object dative (Bernolet & Hartsuiker, 2010), while in German *['zeigen']* it has a preference for the double object dative (Schulte im Walde, 2003). Evidence for a link between specific verbs and structure-preferences provides support for lexicalist theories (Jackendoff, 2002), proposing that syntactic processing is driven by constraints at the lexical level.

This is the first investigation of the influence of verb-specific syntactic preferences on the relationship between syntactic priming effects on response tendencies and effects on response latencies. We found that verb-specific preferences indeed influence syntactic processing: there was an *inverse* effect of preference on syntactic priming effects in response tendencies and a *positive* effect of preference on syntactic priming effects in response latencies.

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Chapter 4

Shared syntax in language production and language comprehension – An fMRI study

During speaking and listening syntactic processing is a crucial step. It involves specifying syntactic relations between words in a sentence. If the production and comprehension modality share the neuronal substrate for syntactic processing then processing syntax in one modality should lead to adaptation effects in the other modality. In the present fMRI experiment, participants either overtly produced or heard descriptions of pictures. We looked for brain regions showing adaptation effects to the repetition of syntactic structures. In order to ensure that not just the same brain regions, but also the same neuronal populations within these regions are involved in syntactic processing in speaking and listening, we compared syntactic adaptation effects within processing modalities (syntactic production-to-production and comprehension-to-comprehension priming) to syntactic adaptation effects between processing modalities (syntactic comprehension-to-production and production-to-comprehension priming). We found syntactic adaptation effects in left IFG (BA 45), left MTG (BA 21) and bilateral supplementary motor area (BA 6) which were equally strong within and between processing modalities. Thus syntactic repetition facilitates syntactic processing in the brain within and across processing modalities to the same extent. We conclude that that the same neurobiological system seems to subserve syntactic processing in speaking and listening.

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Introduction

Successful communication relies on both efficient production and comprehension of language. Is there one integrated system for comprehension and production, or are there two separate systems? How are comprehension and production processes related and which information is shared by the two processing modalities? We can ask these questions in regard to the individual word level or the sentence level, where words are combined in a syntactic structure. The latter is the focus of the current study. Specifically, in this study we investigate whether the neurobiological substrate for coding and processing syntactic representations is shared between speaking and listening.

Naturally, the input for speaking and listening are different. A speaker starts with a communicative intention or a message representation that she wants to communicate to a listener. Over several processing stages, this intention is converted into a sequence of sounds which are articulated. The listener in turn receives this stream of auditory information and has to retrieve its meaning and the intention of the speaker. A core process during both production and comprehension is syntactic processing: specifying the syntactic relations between words in the sentence.

The starting point and the context of syntactic processing are different for production and comprehension. A speaker first converts the intended message into a representation with a specified thematic role structure (i.e., who does what to whom, how, when and where). During syntactic encoding, the thematic role structure is encoded as one particular syntactic structure; for example, a passive transitive structure like "The boy was kissed by the girl yesterday at the cinema". This is achieved by a unification or integration operation on the syntactic information which is connected to the different lexical elements of the message (Vosse & Kempen, 2000). The syntactic building blocks which are used in this unification operation include the syntactic category (e.g., it is a verb) and a frame specifying the possible structural environment (e.g., it takes a subject and an object). During comprehension, this information is retrieved from the recognized words in the input and the sentence structure is then parsed or decoded. From "The boy was kissed by the girl" a listener has to recover that it is a passive transitive structure and that the girl is the agent and the boy the patient of the kissing event.

Certain aspects of syntactic processing thus differ between production and comprehension. During language production, there are many ways for a speaker to convey the same message: one thematic role structure can be expressed by several different syntactic structures. The message that a girl was kissing a boy, can be expressed in the following syntactic structures: "The girl kissed the boy", "The boy was kissed by the girl", or "It is the girl that kissed the boy". A speaker can choose to encode the message as a passive transitive structure when she for instance wants to emphasize the thematic role of the patient (instead of the agent). During language comprehension, the order of the words in the incoming information has been determined by a speaker but it is the listener who has to reconstruct the correct syntactic structure. For the two utterances "The boy kissed the girl" and "The boy was kissed by the girl", the words 'boy', 'kissed' and 'girl' hit the ear of the listener in the same order, but the syntactic structure and the message of the utterance are different. In addition, syntactic assignments are often based on partial information during comprehension, since utterances reach the listener incrementally and therefore ambiguities may arise at any given point in the utterance.

Shared Syntax?

This study aims to answer the question to what extent syntactic encoding and decoding rely on the same neurobiological system. Traditionally, psycholinguists have investigated syntactic processing separately in comprehension and production, sometimes with the assumption that these are two separate systems. For example, Clark and Malt (1984) argued that comprehension must have access to more information than production, since speakers can understand syntactic forms in dialects or in literary texts (e.g., Shakespeare) which they themselves cannot produce. Developmental as well as neuropsychological research is often put forward as evidence for the view that the comprehension and production systems are separate. Developmental research suggests that children can understand more than they can produce, and it has been argued that this is the case for complex syntactic constructions. Children can generally understand syntactic forms well before they begin to produce them (Bates & Bretherton, 1988; Clark & Hecht, 1983; Fraser, Bellugi, & Brown, 1963). Early neuropsychological research uncovered an apparent double dissociation between aphasias: patients with damage to Broca's region are characterized by impaired production and relatively intact comprehension and patients with damage to Wernicke's region show impaired comprehension and relatively intact production (Lichtheim, 1885). This contributed largely to the idea of two separate systems. Although the idea of two separate anatomical systems is outdated, and comprehension as well as production are thought to engage both Broca's and Wernicke's regions to some extent, the idea of two functionally separated systems still commands a sizable following. For example, Grodzinsky (2000) argued that the mechanisms underlying production and comprehension must be (partially) different based on linguistic differences ('tree pruning' versus 'trace deletion') in the production and comprehension deficits of agrammatic patients.

Others have contested the position that there are separate systems for syntax in production and comprehension. Instead, they advocate a unitary system with shared representations or shared processes manipulating representations. Kempen (2000) argued that syntactic encoding and decoding rely on a single processing mechanism operating in different processing contexts. He based his claim on a series of shared characteristics of syntactic processing across modalities: sensitivity to conceptual factors, direct mapping between thematic relations and syntactic relations, incremental processing and determinism (the process ends with one result). In a recent study, Kempen et al. (in press) found evidence for a common grammatical workspace: the mechanism that constructs (in production) or deconstructs (in comprehension) syntactic structures and the short-term storage of the result of this computation is shared between the modalities. Also, the interactive alignment model of dialogue assumes that speakers and listeners share representations, although this does not necessarily imply that the processes operating on them are also shared between modalities (Pickering & Garrod, 2004).

Syntactic Priming between Processing Modalities

The tendency to repeat syntactic structures across utterances is called syntactic priming (Bock, 1986; for a review: Ferreira & Bock, 2006; Pickering & Ferreira, 2008). This phenomenon is a valuable tool to tap into syntactic processing. Syntactic priming leads to facilitated processing, evidenced not only by the increased likelihood to choose the same structure in successive sentences (Bock, 1986), but also by speeded speech onset or reading times for repeated syntactic structures (Smith & Wheeldon, 2001; Traxler & Tooley, 2008) and by repetition effects in the brain measured with fMRI (Menenti, Gierhan, Segaert, & Hagoort, 2011; Weber & Indefrey, 2009).

Syntactic priming from one processing modality to another provides insight into whether syntactic information is shared between modalities. If syntactic information is shared, syntactic processing in one modality should lead to adaptation effects in the other modality. Several behavioural experiments, measuring syntactic persistence across sentences, have shown that syntactic comprehension-to-production priming is possible. Reading or hearing a sentence with a particular syntactic structure increases the likelihood of using the same structure instead of an alternative during the production of a successive sentence (Bock, Dell, Chang, & Onishi, 2007; Branigan, Pickering, & Cleland, 2000; Branigan, Pickering, Liversedge, Stewart, & Urbach, 1995; Potter & Lombardi, 1998). Also evidence for syntactic production-to-comprehension priming has been reported: production of a particular syntactic structure influenced subsequent picture matching for ambiguous descriptions (Branigan, Pickering, & McLean, 2005). These behavioral between-modality syntactic priming experiments seem to suggest that syntactic information is shared between comprehension and production.

However, two issues complicate the picture. First, it is very difficult to compare a behavioral measure of syntactic priming in production (e.g., which structure does a speaker choose?) to a behavioral measure of syntactic priming in comprehension (e.g., how fast is it read?). Therefore, syntactic comprehension-to-production priming effects cannot easily be compared to production-to-comprehension priming effects. The second issue is that - strictly speaking - the results from these behavioral experiments do not rule out that there is a close link between the two modalities while syntactic information is not shared. Comprehension-to-production priming may be influenced by production-based predictions during comprehension (Pickering & Garrod, 2007). Likewise, a production-to-comprehension effect may be influenced by comprehension-based monitoring during production (Levelt, 1989) (although see Branigan et al., 2005).

The present study aims to address these concerns by (1) examining the neuronal substrate of syntactic encoding and decoding using fMRI, with the advantage that the brain activity measured by fMRI serves as common index of the production and the comprehension system, and (2) examining syntactic comprehension-to-production as well as production-to-comprehension priming and comparing these between-modality effects to within-modality effects in one experiment.

Syntactic Processing in the Brain

Do the neural substrates for syntactic encoding and decoding overlap in the brain? Several neuroimaging studies have examined syntactic processing either in comprehension or in production. Investigating language production, Haller et al. (2005) compared sentence generation to word reading and to sentence reading using fMRI. They found effects in Brodmann's areas (BA) 44/45 of the left inferior frontal gyrus, as well as in BA 6, BA 7 and right BA 13. Indefrey et al. (2001) found a neural correlate of syntactic encoding during production in left BA 6 and BA 44 using PET. Additionally, they found evidence for a graded response dependent on the syntactic complexity. In comprehension, Snijders et al. (2009) found the left IFG and left posterior MTG involved in syntactic processing. Noppeney and Price (2004) found a syntactic processing effect in comprehension in the left anterior pole. Also during language comprehension, Ni et al. (2000) found increased activity in left inferior frontal regions for syntactic anomalies. Taken together, these studies mainly found left frontal or temporal regions involved in syntactic encoding or decoding.

Menenti et al. (2011) systematically compared syntactic effects during speaking and listening using an fMRI adaptation paradigm. fMRI adaptation is a phenomenon whereby the BOLD-response in areas sensitive to a stimulus property, for example syntax, is reduced or enhanced when this stimulus property is repeated (Henson, 2003; Segaert, Weber, de Lange, Petersson, & Hagoort, submitted). Popular models on the source of fMRI adaptation are the fatigue model, the sharpening model and accumulation model (Grill-Spector, Henson, & Martin, 2006 for a review). These models propose respectively that neurons in a neuronal population generally respond less strongly when the stimulus property is repeated, that fewer neurons in a neuronal population respond, and that neuronal activity of the neurons peaks earlier. Menenti et al. (2011) found repetition suppression effects for the repetition of syntactic structure in the left posterior MTG and the left IFG during production as well as during comprehension. However, the involvement of the same regions does not necessarily mean that the same neuronal substrate underlies both modalities. Only when the same neuronal populations are involved, one can speak of a shared neuronal substrate. The results of Menenti et al. (2011) can strictly speaking not exclude the possibility that different sets of neuronal populations within a particular brain region underlie syntactic decoding versus syntactic encoding. However, one can conclude that neuronal populations are shared by modalities if we can show that there are between-modality fMRI adaptation effects and that these are equally strong as within-modality fMRI adaptation effects. Irrespective of one's view on the source of fMRI adaptation (fatigue, sharpening or accumulation), fMRI adaptation is assumed to be a consequence of a modulation within the same neuronal population.

In the present event-related fMRI study we aimed to investigate whether there is a common neuronal substrate for syntactic decoding and syntactic encoding. We investigated fMRI adaptation effects to the repetition of syntactic structures, and compared within-modality adaptation effects (syntactic production-to-production and comprehension-to-comprehension priming) to between-modality adaptation effects (comprehension-to-production and production-to-comprehension priming). Comparable within-modality and between-modality syntactic fMRI adaptation effects would suggest that the same neuronal populations are involved in syntactic encoding and syntactic decoding.

Materials and Methods

Participants

Twenty-four right-handed native Dutch speakers without neurological or language impairments and with normal or corrected to normal vision (twelve male; mean age 22 years SD 4.8) participated in the experiment. All participants had attended or were attending university education in the Netherlands. All participants gave written informed consent prior to the experiment and were compensated for their participation.

Stimulus Material

The stimulus material used in this study is largely identical to the material used in Menenti et al. (2011). There were 1728 photographs and 432 auditory sentence descriptions of transitive events. These depicted or described 36 different events such as *kissing, helping* or *strangling* with the agent and patient of this action (Appendix 2.1). The patient of an event is the one who is acted-upon. Each event was enacted in the photographs by four couples (2 x man/woman; 2 x boy/girl), each of these once with the male actor as agent and once with the female actor as agent. Each photograph also had a version with the agent on the left and with the agent on the right. Of each transitive photograph there were two color-coded versions and one grayscale version. Color-coded photographs elicited either active or passive sentence descriptions, because participants were instructed to describe these photographs naming the green actor before the red actor. There was an active version with a green agent and a red patient and a passive version with a red agent and a green patient. The two color-coded versions were used during production trials. During comprehension we presented grayscale photographs, identical to the photographs used in the production trials. During comprehension, photographs were accompanied by auditory sentence descriptions of either active or passive syntactic structures.

There were also 795 photographs and 303 concomitant auditory sentence descriptions serving as fillers. These fillers depicted or described intransitive events such as *singing* and *running* or locative actions such as *standing* and *lying*. The intransitive photographs depicted one actor in green or in red for production trials, or one actor in grayscale (accompanied by an auditory description) for comprehension trials. The locative photographs depicted two objects, or one actor and one object. There were two color-coded versions of the locatives to elicit a locative state (*The ball lies on the table.*) or a frontal locative (*On the table lies a ball.*) for production trials. For comprehension trials there was a grayscale version which would be accompanied by a locative state or a frontal locative description. The intransitive and locative filler items were added to provoke variability in syntactic structures and in the lexical items that participants produced/heard during the experiment. For intransitives, the actors were sometimes famous people, animals or people that could be named by their profession; for locatives, inanimate objects were used.

For the comprehension trials, there were also 97 auditory sentence descriptions that did not match the accompanying grayscale photograph. These mismatch trials were used for attentional control. The descriptions were grammatically correct but did not describe the situation depicted in the photograph. There were mismatch descriptions of intransitive photographs (50%) and of transitive photographs (50%). Semantic and syntactic processing was necessary to be able to detect the mismatches between photograph and auditory description. For example, for a photograph that depicted a man kissing a woman, mismatch descriptions could be: *The man <u>punishes</u> the woman, The <u>girl</u> kisses the woman, The <u>woman</u> kisses the <u>man</u>.* The transitive mismatch items were not target items.

We pre-tested the materials to establish whether the depicted actions were clear and to measure which verb was most commonly used to describe the action. During the actual experiment this verb was presented preceding the photographs.

Experimental Design

We used a 2x2x2x2 design with the factors Syntactic Repetition (syntax was novel vs. repeated compared to the sentence that preceded it), Modality Repetition (processing modality, i.e. speaking versus listening was novel versus repeated compared to the sentence that preceded it), Target Modality (listening vs. speaking) and Target Structure (active vs. passive voice). This resulted in sixteen conditions. The design (8 conditions resulting from crossing the first 3 factors, thus, leaving out the factor target structure) is illustrated in figure 1A.

We used a running priming paradigm where each target item also served as the prime sentence for the next target item (Figure 1B). Therefore, we had an equal amount of active and passive transitive structures and choose to manipulate target structure as a factor. However, we do not expect any differential syntactic repetition effects for actives and passives. Furthermore, while actives sentences are shorter than passives sentences, this is the case in production as well as in comprehension and thus orthogonal to the effects we are interested in.

The verb was always repeated between prime and target. Behavioral syntactic priming studies have shown that verb repetition is critical for syntactic priming within language comprehension (Arai, van Gompel, & Scheepers, 2007; Tooley, Traxler, & Swaab, 2009). Because a crucial aspect of the present study is the comparison of effects within the comprehension modality to between-modality effects, we opted to manipulate syntactic priming while always repeating the verb between prime and target sentence. Because we used a running priming paradigm, the verb was repeated within each block of transitive syntactic structures.

The target items were presented in 80 blocks with an average length of 5 transitive structures (range 3-7 items). The conditions followed each other in a random order that was different for every participant, with two constraints on the order of conditions: The first constraint was that no condition was repeated twice in a row. The second constraint was that a target item with adults was always followed by a target item with children and vice versa, so that there was no lexical repetition other than the verb. In a full list of items presented to the participant, the same action or the same actors could occur several times, but the combination of actors and actions was unique.

The target blocks were alternated with filler blocks with an average length of 3.5 (range 2-5 items). Most of the time the verb was repeated between filler items within one block. For 10 % of the fillers items this was not the case, to bring in some extra variation. A full list of items presented to the participant consisted of approximately 59% transitive structures and 41% fillers. Fifty percent of the items were production items and 50% were comprehension items.

There were 20 items in each of the 16 conditions. In addition to this, in the beginning of each of the 80 blocks of transitive structure items, there was one transitive structure item serving as a prime only item. This increased the number of transitive structure items to 400. Each participant received 680 trials in total (transitive and filler structures), which were divided over two scanning sessions. Each photograph could occur only once in the experiment and every participant saw a different list of items.

Task and Procedure

The stimuli were presented in the following way. First, the verb was presented. Then a photograph followed, which only during comprehension trials was accompanied by an auditory description. The presented verb was colored-coded to let the participant know whether a 'comprehension photograph' or a 'production photograph' would follow. Green verbs preceded colored production photographs and gray verbs preceded black/white comprehension photographs (Figure 1B).

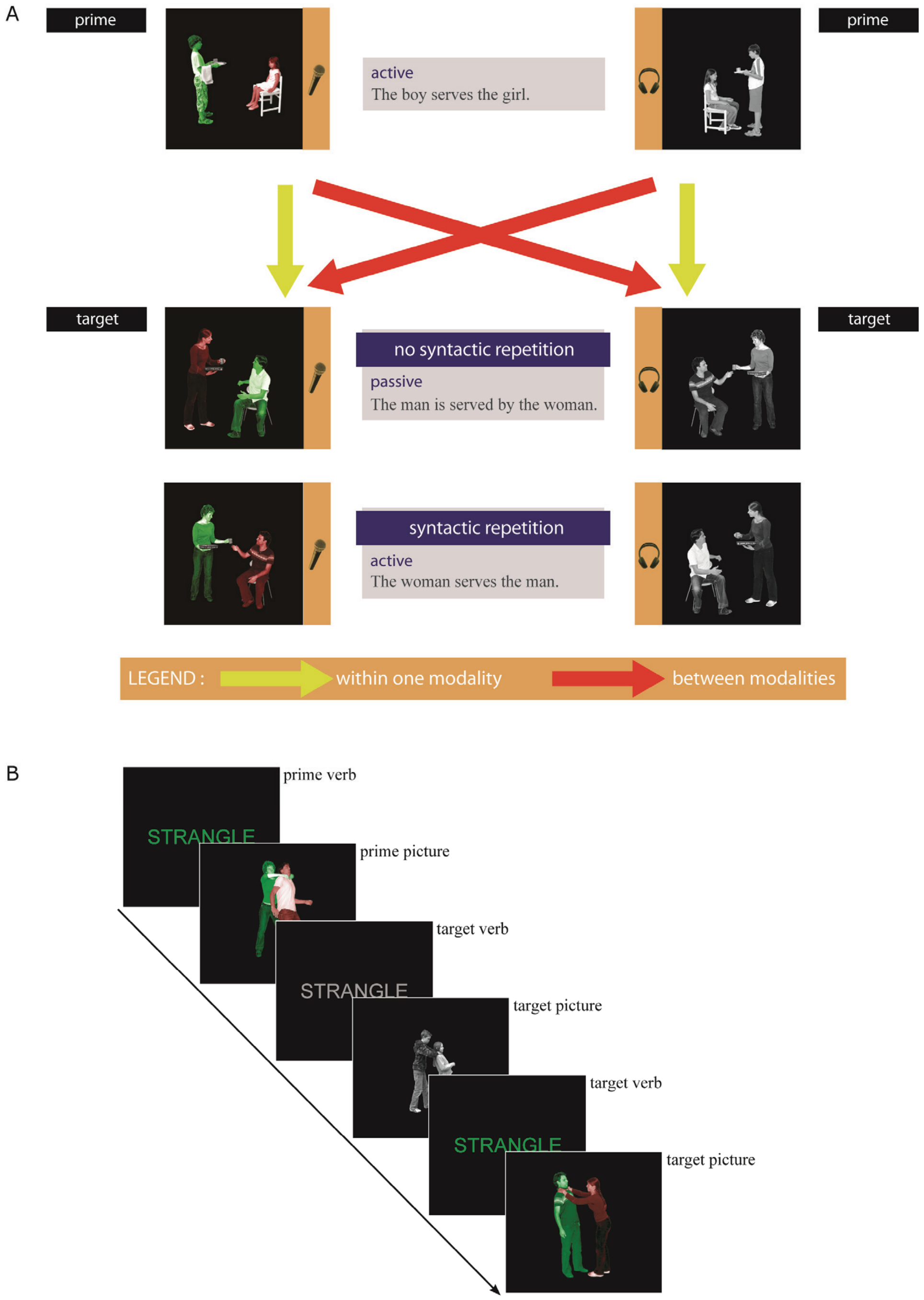

Figure 1. (A) Design and Stimuli. Participants either described colored photographs or listened to descriptions of grayscale photographs, containing action, agent and patient. To guide production, participants were instructed to name the green actor before the red actor. Between subsequent sentences, i.e. prime and target, the syntactic structure and the processing modality could be repeated (for syntax: active-active or passive-passive, for modality: production-production or comprehension-comprehension) or novel (for syntax: active-passive or passive-active, for modality: production-comprehension or comprehension- production). **(B) Procedure.** We used a running priming paradigm where each target item also served as a prime sentence for the next target item. The verb always preceded the photographs. Green verbs indicated a 'production photograph' would follow, gray verbs indicated a 'comprehension photograph' would follow.

Production. During production trials the task was to describe the colored-coded photographs overtly with a short sentence using the presented verb. Participants were instructed to name the green actor before the red actor (traffic light paradigm: Menenti et al., 2011). There was no cue for the participants to start the descriptions; they could freely start whenever they were ready.

Comprehension. During comprehension trials, we used a sentence-picture matching paradigm (Clark & Chase, 1972): participants were presented with a photograph and an auditory description. The photographs were the grayscale version of the ones used in the production trials. The sentence-picture matching paradigm has been used extensively and a recent study supports that it is suitable for studying online situated language comprehension (Knoeferle, Urbach, & Kutas, 2011). By choosing situated paradigms for both production and comprehension trials, we maximize comparability and ensure that the difference between the two only lies in linguistic processing. To make participants pay attention, we instructed them to listen carefully to the description of the black/white photographs and use the response box to indicate when this description was incorrect (the response hand was counterbalanced between participants). During 10% of the comprehension trials there was a mismatch between the description and the photographs. Only for those trials a response had to be given.

Participants completed a short practice block in the scanner before the actual experiment started. The experiment consisted of two runs of 45 minutes. Between the two runs the participants got an anatomical T1 scan and a short break outside the MRI-scanner. Each trial consisted of the following events: first, the verb was presented for 500ms. After an ISI of 500-2500ms the photograph was presented for 2000ms and then the screen turned black. The photograph thus had a fixed presentation time during production as well as comprehension trials. For the production trials the participants started speaking during the presence of the photographs. For the comprehension trials, the auditory sentence was presented following the photograph with an ISI of 0-1000ms, so that we could differentiate between the onset of the photograph and the auditory description in our analyses. The total trial duration of one trial was 7000 ms.

The experimenter coded the participant's production responses online for correctness. Target trials were considered for analysis if during both prime and target trial (1) the correct structure was used and (2) both actors were named accurately and the verb was used correctly.

fMRI Data Acquisition

Participants were scanned with a Siemens 3T Tim-Trio MRI-scanner, using a 12-channel surface coil. To acquire functional data we used parallel-acquired inhomogeneity-desensitized fMRI (Poser, Versluis, Hoogduin, & Norris, 2006). This is a multi-echo EPI sequence, in which images are acquired at multiple TE's following a single excitation (TR = 2.398s; each volume consisted of 31 slices of 3 mm thickness with slice-gap of 17 %; isotropic voxel size = 3.5x3.5x3 mm^3; field of view = 224 mm). The functional images were acquired at following TE's: TE$_1$ at 9.4 ms, TE$_2$ at 21.2 ms, TE$_3$ at 33 ms, TE$_4$ at 45 ms, and TE$_5$ at 56 ms, with echo spacing of 0.5 ms. This entails a broadened T$_2$* coverage, because T$_2$* mixes into the five echoes in a different way, and the estimate of T$_2$* is improved. Accelerated parallel imaging reduces image artefacts and thus is a good method to acquire data when participants are producing sentences in the scanner (causing motion and susceptibility artefacts). However, the number of slices did not allow acquisition of a full brain volume in most participants. We made sure that the entire temporal and frontal lobes were scanned because these were the regions where the fMRI adaptation effects of interest were expected. This meant that data from the superior posterior frontal lobe and the superior parietal lobe (thus data from the top of the head) were not acquired in several participants. A whole-brain high resolution structural T1-weigthed MPRAGE sequence was performed to characterize participants' anatomy (TR = 2300 ms, TE = 3.03 ms, 192 slices with voxel size of 1 mm^3, FOV = 256), accelerated with GRAPPA parallel imaging.

Data Analysis

Preprocessing. fMRI data were preprocessed using SPM5 (Friston, Ashburner, Kiebel, Nichols, & Penny, 2007). The first 5 images were discarded to allow for T_1 equilibration. Then the five echoes of the remaining images were realigned to correct for motion artefacts (estimation of the realignment parameters is done for one echo and then copied to the other echoes). The five echoes were combined into one image with a method designed to filter task-correlated motion out of the signal (Buur, Poser, & Norris, 2009). First, echo two to five (i.e., TE_2, TE_3, TE_4 and TE_5) were combined using a weighting vector with the weights depending on the measured differential contrast to noise ratio. The time course of an image acquired at a very short echo time (TE_1) was then used in a linear regression as a voxelwise regressor for the other image (i.e., the result of combining TE_2, TE_3, TE_4 and TE_5) in the same echo train acquired with high BOLD sensitivity. The resulting images were coregistered to the participants' anatomical volume, normalized to MNI space and spatially smoothed using a 3D isotropic Gaussian smoothing kernel (FWHM = 8mm).

Whole-Brain Analysis. We performed 1st and 2nd level statistics using the general linear model framework of SPM5 (Friston et al., 2007). Our 2 x 2 x 2 x 2 design resulted in 16 conditions and thus 16 main regressors for the statistical analysis of the fMRI data. We used an implicit baseline. In the 1st level linear model, we modeled the individual start time of the photograph (during production trials) or the auditory sentence description (during comprehension trials). We modeled the hemodynamic response function only as related to these onsets and set the duration as a constant event. Separate regressors were included for the verbs, photographs during comprehension trials, fillers items, items which were only primes and incorrect responses. The events of the model were convolved with the canonical hemodynamic response function provided by SPM5. Also the temporal derivatives were included in the model. Furthermore, six motion parameters (realignment parameters: translation along, and rotation around, the x, y and z axes) and two parameters which correct for global intensity fluctuations (compartment signal parameters: white matter and cerebral spinal fluid; Verhagen, Dijkerman, Grol, & Toni, 2008) were added as regressors. For the 2nd level random-effects analysis we used the beta-images of the 16 main regressors. The cluster size was used as the test statistic and only clusters significant at $P < 0.05$ corrected for multiple non-independent comparisons are reported. Local maxima are also reported for all clusters with their respective Z-values.

Region of Interest (ROI) Analysis. We performed an ROI analysis in the activation clusters for which we found a main effect of syntactic repetition in the whole-brain analysis. The sole aim of the ROI analysis was to establish with higher sensitivity than in the whole-brain analysis whether there was an interaction between the effect of syntactic repetition and modality change in these clusters. We thus tested an interaction effect which is orthogonal to the main effect that defined the ROI, thereby avoiding biasing the analyses (Kriegeskorte, Simmons, Bellgowan, & Baker, 2009). Of each cluster we calculated the average time courses using Marsbar (http://marsbar.sourceforge.net/). For the ROI analysis at the second level we carried-out a repeated measures ANOVA with the factors syntactic repetition, modality repetition, target modality and target structure on the subject contrast values using SPSS. We corrected for multiple comparisons by using a threshold for significance of $P = .05$ divided by the number of clusters showing a main effect of syntactic repetition in the whole-brain analysis. In Appendix 1, we describe the methods and results of ROI analyses in two clusters, one in left IFG and one in left MTG, found by Menenti et al. (2011) for syntactic processing in comprehension and in production.

Results

Behavioral performance

In the production task, participants responded correctly on 96% of the trials. In the comprehension task, the participants detected on average 92% of the mismatch trials. The average d-prime was .91. These results show that participants performed well on both tasks.

Whole-Brain Analysis

For the whole brain comparisons, we used a cluster-level threshold corrected for multiple comparisons of $P < .05$ and an uncorrected voxel-wise threshold of $P < .001$ (Figure 2 and 5, Table 1 and 2).

As displayed in Figure 2 and Table 1, there were several regions showing an adaptation effect to repeated syntax (conditions with novel syntax minus conditions with repeated syntax): the left MTG (BA 21), left IFG (BA 45, extending into BA 47) and bilateral supplementary motor area (BA 6). These regions are thus less activated for sentences with a repeated syntax than for sentences with novel syntax. That is, they show repetition suppression for syntax. We tested whether there was an interaction between syntactic repetition and modality repetition (i.e. whether there was less syntactic adaptation across processing modalities than within processing modalities). Crucially, there was no evidence of such an interaction. We also tested whether there was an interaction between syntactic repetition and target modality (i.e. whether there was less syntactic for comprehension targets than for production targets). There was no evidence of such an interaction. There were no repetition enhancement effects. In Appendix 1 (Figure 5 and Table 2) we describe the network of regions that is activated more during production than comprehension, the network of regions that is activated more during comprehension than production, and the network of regions involved in switching between processing modalities. In all three cases we took the conditions with syntactic repetition and without syntactic repetition together.

ROI Analysis

In each cluster that showed an adaptation effect for syntactic repetition, we checked with an ROI analysis whether there was an interaction between the size of the syntactic adaptation effect and modality change. These analyses confirmed the results of the whole-brain analysis: there was no interaction between the adaptation effect for syntactic

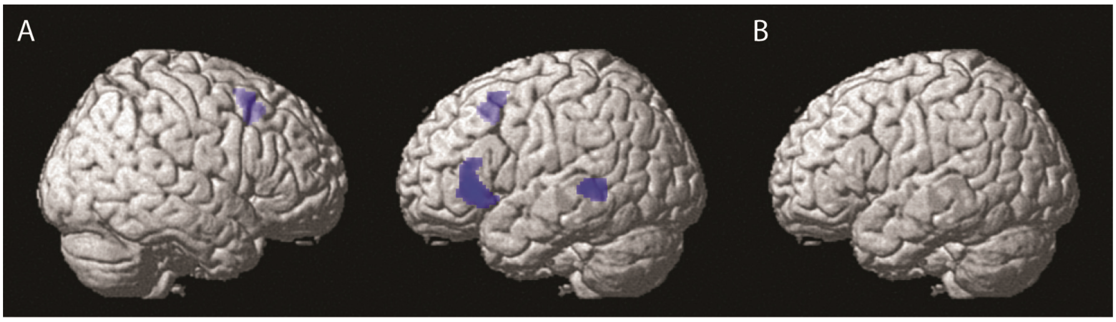

Figure 2. Whole brain results (see also Table 1). (A) The adaptation effects for syntax repetition. In left MTG, left IFG and supplementary motor area there was a repetition suppression effect for repeated compared to novel syntactic structures. (B) Interaction between syntax repetition and modality repetition. No regions showed an interaction between syntax repetition and modality repetition.

Table 1. The effect of syntactic repetition

Anatomical label	BA	global and local maxima			cluster-level		voxel-level
		x	y	z	K	P(corr)	Z
Main effect syntax repetition (no syntactic repetition > syntactic repetition)							
L mid temporal	21	-50	-40	2	197	.023	4.92
L inf frontal (pars orbitalis)	47	-42	24	-2	567	.000	4.07
L inf frontal (p. triangularis)	45	-40	32	8			3.67
L inf frontal (p. triangularis)	45	-40	26	16			3.60
L supplementary motor area	32/6	-10	20	46	190	.027	3.97
L supplementary motor area	6	-2	14	56			3.58
R supplementary motor area	32/6	8	18	50			3.51
Interaction syntax repetition x modality change							
no significant clusters							
Interaction syntax repetition x target modality							
no significant clusters							

Note: Listed are the MNI-coordinates for three local maxima for each significant cluster in the relevant comparisons (*P*<.05 corrected cluster-level, threshold *P*<.001 uncorrected voxel-wise). Anatomical labels are derived from the Automated Anatomical Labeling map (Tzourio-Mazoyer et al., 2002) and from Brodmann's atlas.

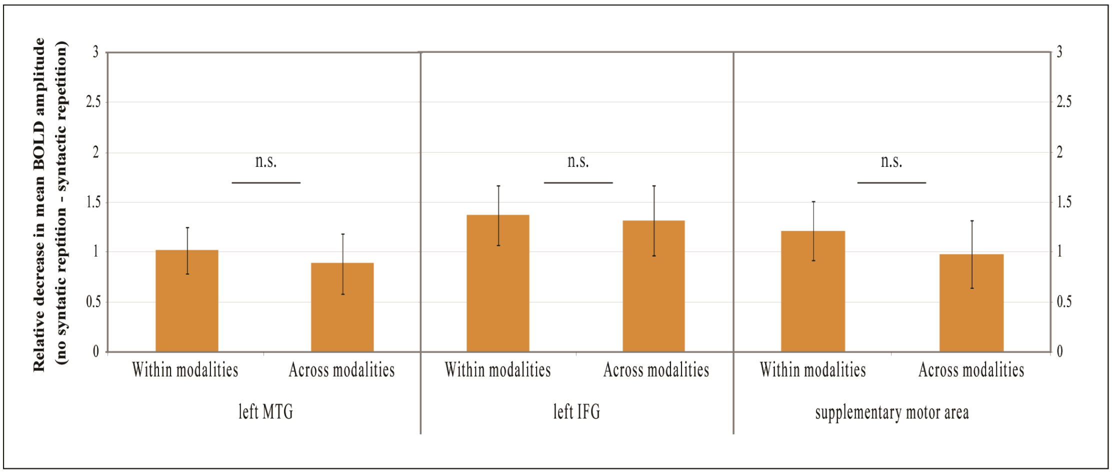

Figure 3. ROI analysis. ROI analysis in the three clusters showing a main effect of syntactic repetition - left MTG, left IFG and supplementary motor area - confirmed that there was no differential repetition suppression effect for syntactic structures within and across processing modalities.

repetition and within vs. between modality priming. In all three ROIs the interaction was clearly absent: left MTG ($F_{1,23}$ = .09, *P* = .77), left IFG ($F_{1,23}$ = .016, *P* = .90), the supplementary motor area ($F_{1,23}$ = .35, *P* = .56). Figure 3 illustrates for each ROI the relative decrease in mean BOLD amplitude for repeated syntax compared to novel syntax, separately for the effect within a processing modality and the effect across processing modalities.

Discussion

In this study we investigated whether the neuronal infrastructure for coding and processing syntactic representations is shared between language production and language comprehension. We tested this by comparing fMRI adaptation effects for the repetition of syntactic structures within and between processing modalities. While within-modality syntactic adaptation effects in comprehension and production show that the same brain regions are involved, only comparable between-modality adaptation effects indicate that the neuronal populations within these regions are shared. Our results demonstrate that syntactic repetition indeed facilitates syntactic processing in the brain within and across processing modalities to the same extent. Our results disclose the following organizational principles of syntactic processing in comprehension and production: (i) not just the same brain regions, but the same neuronal populations subserve syntactic encoding in production and syntactic decoding in comprehension. Hence, there is a shared neuronal substrate; (ii) this neuronal substrate involves left IFG (BA 45), left MTG (BA 21) and bilateral supplementary motor area (BA 6).

Left IFG (BA 45), left MTG (BA 21) and bilateral supplementary motor area (BA 6) are regions that have been found to support syntactic encoding or decoding in previous research (Haller et al., 2005; Indefrey et al., 2001; Lee & Newman, 2010;

Menenti et al., 2011; Snijders et al., 2009). Previous work supports a division of labor between left IFG and left MTG: while the MTG supports the retrieval of lexical-syntactic information from memory, left IFG supports the unification of this information into multi-word utterances. (Hagoort, 2003, 2005; Snijders et al., 2009). Left IFG and the lateral prefrontal cortex are particularly suited for actively maintaining, manipulating and integrating information in general (Fuster, 2001). They might provide the appropriate neurobiological infrastructure for unification processes on syntactic information. The buildings blocks of information used in this unification process, are proposed to be lexical-syntactic frames (Vosse & Kempen, 2000). These frames are stored in long-term memory and it is left MTG that is involved in the storage as well as retrieval of this lexical-syntactic information.

In the present study we also found bilateral involvement of supplementary motor area (BA32/6). Our activations lie in pre-SMA, the region of SMA which is more anterior than the coronal plane passing through the anterior commisure (Picard & Strick, 2001). More posterior than the level of the anterior commisure lies SMA proper. Unlike SMA proper, which is connected to primary motor cortex, pre-SMA has strong connections to the dorsolateral prefrontal cortex (Bates & Goldman-Rakic, 1993; Geyer, Matelli, Luppino, & Zilles, 2000). Therefore, pre-SMA is functionally considered to be part of the prefrontal cortex and has been associated with a variety of cognitive tasks (Picard & Strick, 2001). Pre-SMA has been associated with establishing and retrieving sensori-motor associations at an abstract level which is independent of the input modality and more generally with processing or maintaining relevant sensory information (Picard & Strick, 2001). Pre-SMA has furthermore been associated with internally guided word generation at the level of single word production (Alario, Chainay, Lehericy, & Cohen, 2006; Crosson et al., 2001) and encoding of syllable frames and their serial position (Bohland & Guenther, 2006; Ghosh, Tourville, & Guenther, 2008). The role of pre-SMA in our study might lie in the process of sequencing syllable structures. The sequence of syllables for two passives is more common than the sequence for an active and a passive. Likewise, the sequence of syllables for two actives is more common than the sequence for an active and a passive. For instance, for the verb *meten* in Dutch (which translates to *to measure* in English), two passives would share the following sequence of syllables: *'wordt gemeten door'*. Two actives would share the following sequence of syllables: *'meet'*. In other words, when a syntactic structure is repeated also the sequence of syllable frames is in part repeated. This may be the reason we find fMRI adaptation effects for repeated syntactic structures in pre-SMA.

We investigated the effect of syntactic repetition while always repeating the verb between prime and target sentence. Behavioral syntactic priming studies have shown that verb repetition is critical for syntactic priming within language comprehension (Arai et al., 2007; Tooley et al., 2009). To guarantee that we could compare effects within the comprehension modality to between-modality effects, we needed to establish syntactic repetition effects in the brain within the comprehension modality. A future study would be needed to confirm that the present results are replicated even in the absence of verb repetition.

From our finding that there is a shared neuronal substrate for syntactic processing in speaking and listening, we can infer that there is a shared cognitive system with shared representations (Pickering & Garrod, 2004) and/or processes manipulating these representations (Kempen, 2000). Therefore, theories of syntactic processing in the comprehension or production domain that propose modality specific aspects are problematic. Our findings do not entirely exclude the possibility that there are some differences between syntactic encoding and syntactic decoding. There may be a dissociation that has to do with the difference in direction between syntactic encoding and decoding. When constructing syntactic structures, a speaker knows the concepts and thematic role structure, because she has determined them herself. The difficulty lies more in specifying the word order. On the other hand when deconstructing syntactic structures, the word order is given but the difficulty lies more in reconstructing the thematic role structure. So there may be a difference between syntactic encoding and decoding in terms of where difficulties or ambiguities are likely to arise. Moreover, in comprehension one might be able to bypass full syntactic decoding in the presence of semantic, lexical and non-linguistic information (Indefrey, Hellwig, Herzog, Seitz, & Hagoort, 2004). In production one usually cannot bypass syntactic encoding.

Developmental findings suggesting that there are differences in understanding versus producing syntactic structures (Bates & Bretherton, 1988; Clark & Hecht, 1983; Fraser et al., 1963), indicate that we should leave open the possibility that there are some differences between deconstructing and constructing syntax, but these are not final arguments in favor of such differences. These developmental findings might be due to the fact that we, children as well as adults, can understand a lot without paying attention to syntax. During comprehension, meaning can be derived from purely lexical information and from the context, in combination with general conceptual world knowledge; this is the case for children and also for adults listening to dialects or foreign languages they only know to some extent.

In conclusion, there is an extensive amount of overlap in syntactic decoding and encoding. There are good arguments and evidence that the workspace for the assembly and short-term storage of syntactic structures is shared between processing modalities (Kempen et al., in press; Vosse & Kempen, 2000). In the present study we have shown that there is a shared neural substrate of syntactic encoding in production and syntactic decoding in comprehension. This substrate involves left IFG (BA 45) and left MTG (BA 21). The idea of a shared processor for syntax thus deserves sincere attention in future research.

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Chapter 5

Lexically boosted syntactic priming as measured by fMRI adaptation during language production and language comprehension

Syntactic priming refers to the facilitated processing of a sentence with the same structure as a sentence processed shortly before. Findings demonstrating a “lexical boost” of syntactic priming due to verb repetition provide support for lexicalist grammar frameworks. We investigated whether the neural activity in regions subserving syntactic processing reveals lexically boosted syntactic priming effects. Specifically, we measured the extent of fMRI adaptation to repetition of active and passive voice sentences with and without verb repetition, during production and comprehension. In the lIFG and lMTG we observed the same pattern of results. There was a lexical boost of fMRI adaptation to syntactic repetition of sentences in active voice. We observed fMRI adaptation to syntactic repetition of sentences in passive voice independently of verb repetition. We discuss possible explanations for the difference in results between active and passive voice sentences. The processing modality (production vs. comprehension) did not modulate the results.

Adapted from: Segaert, K., Kempen, G., Petersson, K. M., & Hagoort, P. (submitted). Lexically boosted syntactic priming as measured by fMRI adaptation during language production and language comprehension.

Introduction

This study examines the interplay between syntactic and lexical (i.e., word) processing during sentence production and sentence comprehension, focusing on effects of syntactic priming. Syntactic priming is the tendency to reuse syntactic structures across utterances. This tendency is often strengthened when not only the syntactic structure is repeated but also the lexical head of the structure: this is the so-called lexical boost. Specifically, we investigate whether such lexical boost effects manifest themselves in brain activity measured with functional MRI.

Syntactic priming and the lexical boost

The tendency for speakers to repeat syntactic structures across successive utterances was observed long ago (Kempen, 1977; Levelt, 1989). The phenomenon is called syntactic priming or structural priming (Bock, 1986; for a review: Ferreira & Bock, 2006; Pickering & Ferreira, 2008). It has been exploited extensively as a tool to tap into syntactic processing, due to the facilitatory effect it exerts on syntactic processing. In language production, syntactic priming is reflected in the increased likelihood to choose the same structure in consecutive sentences (Bock, 1986) and by faster speech onsets for repeated syntactic structures (Corley & Scheepers, 2002; Segaert, Menenti, Weber, & Hagoort, 2011; Smith & Wheeldon, 2001). In both the comprehension and the production modalities, syntactic priming has been demonstrated through an fMRI adaptation effect called repetition suppression (Menenti, Gierhan, Segaert, & Hagoort, 2011; Weber & Indefrey, 2009).

Several behavioural studies have observed that the size of the syntactic priming effect can be increased by repeating not only the syntactic construction but also the lexical item that functions as head of that construction: the so-called lexical boost. For example, consider the two alternative dative constructions in English: the Prepositional-Object dative (e.g. *The teacher gave the book to the student*) and the Double-Object dative (e.g., *The teacher gave the student the book*). The facilitatory effect of syntactic priming on processing consecutive Prepositional-Object datives is "boosted" if the first sentence (the "prime") and the second sentence (the "target") contain the same ditransitive head verb (compared to repetition of this construction with a different verb). Several production studies investigating the likelihood of choosing the same versus an alternative construction (Branigan, Pickering, & Cleland, 2000; Hartsuiker, Bernolet, Schoonbaert, Speybroeck, & Vanderelst, 2008; e.g. Pickering & Branigan, 1998) have demonstrated that syntactic priming effects are "boosted" when the head word is repeated.

Behavioural studies of syntactic priming and the lexical boost effect during language comprehension reveal a somewhat different picture. Syntactic priming is rarely observed in the absence of verb repetition (Arai, van Gompel, & Scheepers, 2007; Branigan, Pickering, & McLean, 2005; Tooley, Traxler, & Swaab, 2009; Traxler & Tooley, 2007). However, Thothathiri and Snedeker (2008) report lexically-independent syntactic priming during comprehension. Syntactic priming during language comprehension is typically measured using picture matching, ERPs or eye movements.

It has been suggested that the different directionality of production versus comprehension processes is responsible for the differential impact of lexical repetition on syntactic priming in production and comprehension. For instance, Arai et al. (2007) and Tooley et al. (2009) suggest that comprehenders can access words before computing the syntactic structure, while speakers may choose a syntactic structure before accessing the head word of the syntactic construction (usually the verb of a clause or Verb Phrase).

Findings demonstrating the presence of a lexical boost can be explained by a lexically mediated syntactic priming mechanism such as the residual activation mechanism proposed by Pickering et al. (Cleland & Pickering, 2003; Pickering & Branigan, 1998). The residual activation theory assumes that when a syntactic frame has been activated recently, residual activation will promote repeated selection of this frame. When the head word of a construction (i.e., the verb of a ditransitive or transitive clause) is repeated as well, there is residual activation also of the link between the verb and the syntactic frame, thus boosting syntactic priming effects. Evidence for a lexical boost of syntactic priming is difficult to reconcile with a syntactic priming mechanism which is not lexically mediated, for example, the implicit-learning mechanism proposed by Chang et al. (Chang, Dell, & Bock, 2006; Chang, Dell, Bock, & Griffin, 2000).

More evidence for lexical influences on syntactic priming

Syntactic preferences and syntactic restrictions associated with specific verbs have been found to influence syntactic processing. For example, most ditransitive English verbs can occur in the Prepositional-Object dative as well as the Double-Object dative construction. However, the strength of the associations with these alternative constructions varies across lexical items. For instance, the verb *to sell* prefers the Prepositional-Object dative construction while *to show* is more common in the Double-Object dative construction (Gries & Stefanowitsch, 2004). These verb-specific syntactic preferences affect syntactic processing in comprehension (Trueswell & Kim, 1998; Trueswell, Tanenhaus, & Kello, 1993) and in production (Bernolet & Hartsuiker, 2010; Jaeger & Snider, 2007; Segaert, Weber, Cladder-Micus, & Hagoort, submitted). Moreover, single verbs presented in isolation have been found to change the likelihood for the speaker to select one alternative structure instead of the other (Melinger & Dobel, 2005; Salamoura & Williams, 2006). Melinger and Dobel (2005) used Dutch and German ditransitive verbs that could take only one of the two dative constructions (cf., the English verb *to donate*, which only takes the Prepositional-Object dative). They presented the participants with such an infinitival verb as prime, followed by the picture of an action that could be described in terms of a verb compatible with either dative construction. Such an isolated prime biased the participants' descriptions towards the construction associated with the prime verb.

Lexicalist grammars

Findings demonstrating the influence of lexical factors on syntactic priming, such as the observed presence of a lexical boost due to verb repetition, provide an argument for so-called lexicalist grammar frameworks. Lexicalist grammar formalisms have found increasing support in recent years (Jackendoff, 2002). In these frameworks, the distinction between traditional grammar rules and lexical items is blurred or disappears completely. Lexicalist grammars propose that syntactic information is retrieved from the lexicon, the repository of information associated with individual lexical items, including their syntactic information (for verbs: whether they are intransitive, transitive or ditransitive, and in the latter case, which dative construction(s) they govern).

One computationally explicit lexicalist grammar is the Performance Grammar of Kempen & Harbusch (2002, 2003). Here we sketch how Performance Grammar is used in a model of syntactic parsing called Unification-Space (Vosse & Kempen, 2000, 2009). For every incoming word a "lexical frame" is retrieved from the Mental Lexicon (long-term memory). These elementary syntactic trees specify the possible syntactic environment of a given word (e.g., a finite transitive verb combines with a subject and a direct object obligatorily, and with adverbial modifiers optionally). Every retrieved lexical frame is entered into the Unification Space—the workspace where the retrieved lexical frames are unified into a syntactic tree spanning the entire input sentence. The unification process causes the lexical frames to be linked or bound together in such a way that agreement and word-order constraints are met. The strength of the unification links between frames is dynamic and may vary as new information enters the Unification-Space. Selection among alternative unification options occurs through lateral inhibition, causing the processing system to settle on a single stable set of unification links (i.e., one resulting syntactic tree).

Brain regions

Syntactic processing. Several neuroimaging studies have examined the brain regions involved in syntactic processing, in comprehension and/or in production. Investigating language production, Haller et al. (2005) found effects in Brodmann's areas (BA) 44/45 of the left inferior frontal gyrus, as well as in BA 6, BA 7 and right BA 13. Indefrey et al. (2001) found a neural correlate of syntactic encoding during production in left BA 6 and BA 44 using PET. In comprehension, Snijders et al. (2009) found the left inferior frontal gyrus (IFG) and left posterior middle temporal gyrus (MTG) involved in syntactic processing. Menenti et al. (2011) and Segaert et al. (2011) found the left IFG and left posterior MTG involved in syntactic processing, in comprehension as well as production. Noppeney and Price (2004) observed a syntactic processing effect in comprehension in the left anterior temporal pole. Also during language comprehension, Ni et al. (2000) found increased activity in left inferior frontal regions for syntactic anomalies. Taken together, these studies show that left inferior frontal and posterior middle temporal regions primarily subserve the syntactic aspects of language production and comprehension.

Additionally, previous work attests to a specific division of labor between the left IFG and the left MTG: while the MTG supports the retrieval of lexical-syntactic information from long-term memory, the left IFG supports the unification of this information into syntactic sentence-level representations (Hagoort, 2003, 2005; Snijders et al., 2009). The left IFG and the lateral prefrontal cortex support the active maintenance, manipulation and integration of information in general (Fuster, 2001), thus providing the appropriate neurobiological infrastructure for unification processes acting on syntactic information. Within the framework of Performance Grammar, the syntactic building blocks used in the unification process consist of lexical frames (Vosse & Kempen, 2000) stored in the Mental Lexicon, which presumably is subserved by the left MTG (Snijders et al., 2009).

Where lexical and syntactic processing meet. Menenti et al. (2011) investigated syntactic as well as lexical effects, during speaking as well as listening. They found the left IFG and the left posterior MTG to be involved in syntactic processing as well as lexical processing. Keller, Carpenter and Just (2001) found that during language comprehension lexical and syntactic processes interact in left-hemisphere regions including inferior frontal, inferior parietal, posterior middle frontal and superior/middle temporal regions. Newman, Ratliff et al. (2009) observed that lexical priming of the verb facilitates sentence-level processing during comprehension and is accompanied by repetition suppression in left BA 44.

The present study

In the present event-related fMRI study, we investigated whether the neural activity in brain regions subserving syntactic processing reveals a lexical boost of syntactic priming effects. Specifically, during sentence production and comprehension, we measured the extent of fMRI adaptation to repetition of verb-headed syntactic constructions with vs. without repetition of the head verb. FMRI adaptation is a phenomenon whereby the BOLD-response in areas sensitive to a stimulus property, for example a syntactic property, is reduced or enhanced when this stimulus property is repeated (Henson, 2003; Segaert, Weber, de Lange, Petersson, & Hagoort, submitted). This is the first study to investigate whether the lexical boost can be measured at the neuronal level during speaking as well as listening, and to compare the size of lexical boost effects in these two modalities of spoken language use.

Materials and Methods

Participants

Thirty-eight right-handed native Dutch speakers without neurological or language impairments and with normal or corrected-to-normal vision (18 male; mean age 22 years, SD 4.3) participated in the experiment. All participants were university educated. Participants gave written informed consent prior to the experiment and were compensated for their participation. Fourteen participants (seven male; mean age 23 years SD 5.8) participated only in the No-Verb-Repetition condition of the between-subject factor Verb Repetition. Fourteen participants (six male; mean age 22 years SD 3.3) participated only in the Verb-Repetition condition of this factor. Ten participants (five male; mean age 20 years SD 2.3) participated in both conditions of the Verb-Repetition factor.

Stimulus Material

We investigated syntactic priming of active and passive voice constructions headed by transitive Dutch verbs. The stimulus material used in this study is largely identical to the material used in Menenti et al. (2011). There were 1728 photographs and 432 auditory sentence descriptions of transitive events. These depicted 36 different events such as *kissing, helping* or *strangling* with the agent and patient of this action (see Appendix). The patient of an event is the one who is acted on. Each event was enacted in the photographs by four pairs (twice man/woman; twice boy/girl), each of these once with the male actor as agent and once with the female actor as agent. Each photograph also had one version with the agent on the left and one version with the agent on the right. Of each photograph depicting a transitive event, there were two color-coded versions and one grayscale version. Color-coded photographs elicited either active or passive sentence descriptions: participants were instructed to describe these photographs naming the green actor before the red actor. There was an active version with a green agent and a red patient, and a passive version with a red agent and a green patient. The two color-coded versions were used during production trials. During comprehension, we presented grayscale photographs (identical to the photographs used in the production trials) and the photographs were accompanied by auditory sentence descriptions of either active or passive syntactic structures. Passive syntactic structures in Dutch have (at least) two possible word orders (two different linearizations of the Dutch *by*-phrase). The more frequent word order places the *by*-phrase before the clause-final head verb (*De vrouw wordt door de man gekust* 'The woman is by the man kissed'); the less frequent word order places the *by*-phrase after the head verb (*De vrouw wordt gekust door de man* 'The woman is kissed by the man'). The auditory sentence descriptions for passive sentences used the more frequent word order.

There were also 795 photographs and 303 concomitant auditory sentence descriptions serving as fillers. These fillers depicted or described intransitive events such as *singing* and *running* or locative actions such as *standing* and *lying*. The intransitive photographs depicted one actor in green or in red for production trials, or one actor in grayscale (accompanied by an auditory description) for comprehension trials. The locative photographs depicted two objects, or one actor and one object. For production trials, there were two color-coded versions of the locatives serving to elicit a locative state (*De bal ligt op de tafel* 'The ball lies on the table') or a frontal locative sentence (*Op de tafel ligt de bal* 'On the table lies the ball'). For comprehension trials, there was a grayscale version which would be accompanied by a locative state or a frontal locative description. The intransitive and locative filler items lent variability to the syntactic structures and the lexical items that participants produced/heard during the experiment. For intransitives, the actors were sometimes famous people, animals or people that could be named by their profession; for locatives, inanimate objects were used.

For the comprehension trials, there were also 97 auditory sentence descriptions that did not match the accompanying grayscale photograph. These mismatch trials were used for attention control. The descriptions were grammatically correct but did not describe the situation depicted in the photograph. There were mismatch descriptions of intransitive photographs (50%) and of transitive photographs (50%). Semantic and syntactic processing was necessary to be able to detect the mismatches between photograph and auditory description. For example, given a photograph that depicted a man kissing a woman, mismatch descriptions could be: *The man punishes the woman, The girl kisses the woman, The woman kisses the man*. The transitive mismatch items were not target items. We pre-tested all materials in order to establish whether the depicted actions were clear, and to determine which verb was used most often to describe the action. This verb was presented preceding the photographs in the course of the actual experiment.

Experimental Design

We used a 2x2x2x2x2 design with the following within-subject factors: (1) voice of the target sentence (active or passive); (2) syntactic repetition (voice of the produced/heard clause in prime and target sentence was same or different); (3) processing modality of the prime (speaking or listening); (4) processing modality of the target (speaking or listening). As between-subjects factor we manipulated whether the head verbs of prime and target sentences were identical or different. This resulted in thirty-two conditions. The design is illustrated in figure 1.

We used a running priming paradigm where each target item also served as the prime sentence for the next target item (Figure 2). Since Verb Repetition was manipulated as between-subject factor, half of the lists of items contained blocks in which the verb was always repeated between prime and target, and the other half of the lists contained blocks in which the verb was never repeated between prime and target. The target items were presented in 80 blocks with an average length of 5 transitive

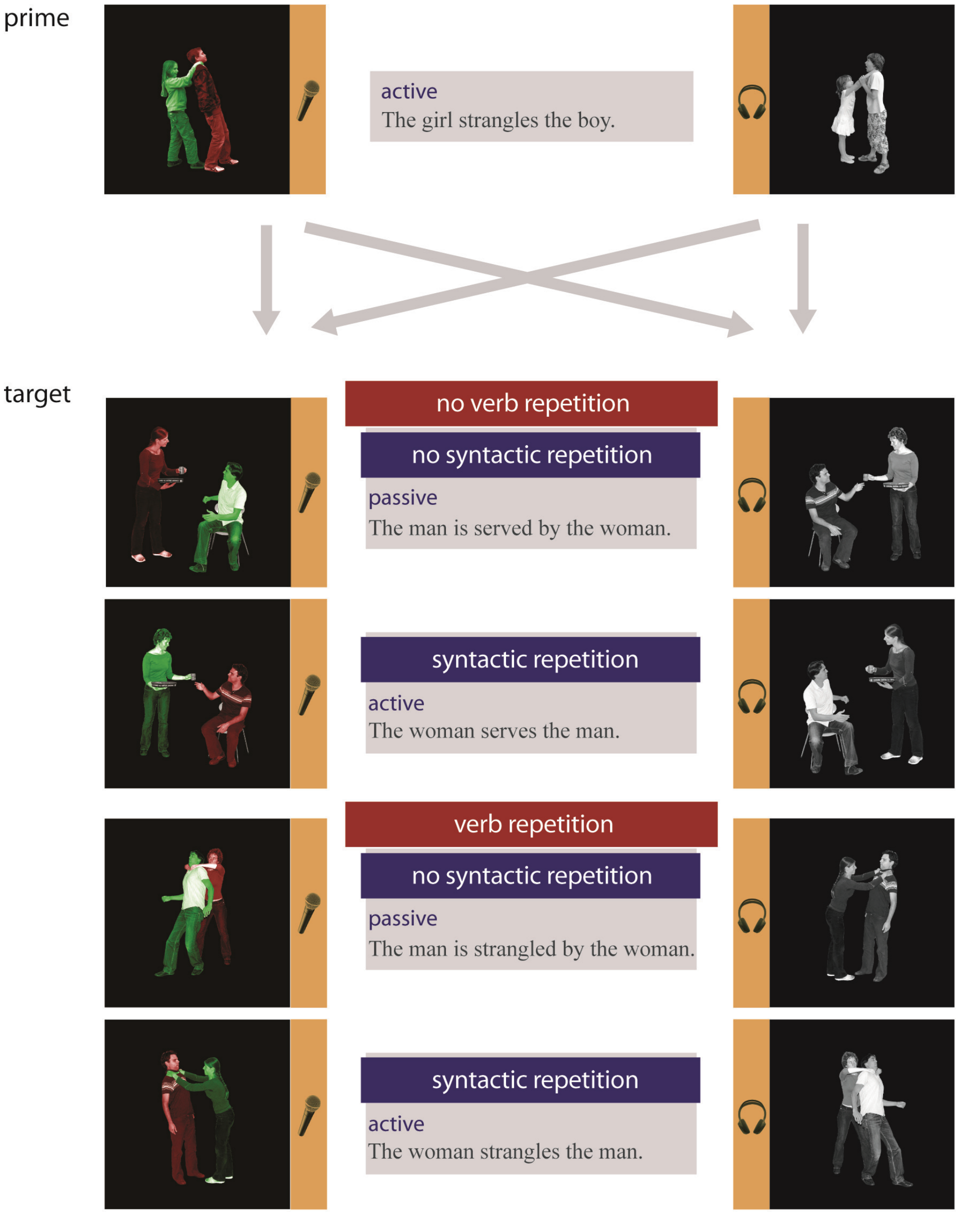

Figure 1. Design of the experiment. Participants either described colored photographs or listened to descriptions of grayscale photographs, containing action, agent and patient. On production trials, the syntactic structure of the sentence was manipulated by instructing participants to refer to the green person before the red person. For each prime trial, eight possible targets trials were created. These target trials differed from each other in the following ways. Within-subjects factors were: (1) voice of the target sentence (active or passive); (2) syntactic repetition (voice of the produced/heard clause in prime and target sentence was same or different); (3) processing modality (all four combinations of producing or hearing the prime and the target were tested). As between-subjects factor we manipulated whether the head verbs of prime and target sentences were identical or different. To examine the role of syntax, we compared trials using novel syntax with trials using repeated syntax. To examine the role of verbs, we compared target trials using novel verbs with target trials using repeated verbs. Example words and sentences have been translated from Dutch.

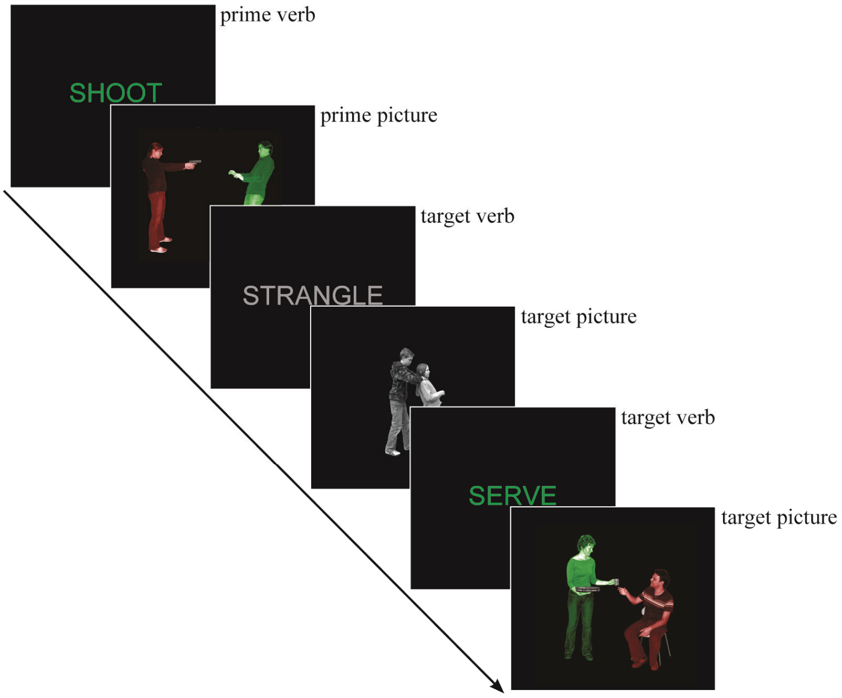

Figure 2. Sample sequence of trials. We used a running priming paradigm where each target item also served as a prime sentence for the next target item. The verb always preceded the photographs. Green verbs indicated a 'production photograph' would follow, gray verbs indicated a 'comprehension photograph' would follow. In production trials participants were required to produce a sentence describing the photograph using the verb they had been shown and referring to the green person before the red person. In comprehension trials, participants saw a photograph of an action being performed and heard a sentence describing the picture in either the active or the passive voice. Subjects pressed a button when they detected a mismatch between the spoken description and the picture. The procedure is illustrated for a list in the condition without verb repetition.

structures (range 3-7 items). The conditions followed each other in a random order that was different for every participant, with two constraints on the order of conditions: no condition was repeated twice in a row; and a target item with adults was always followed by a target item with children and vice versa, so that in the lists with verb repetition there would be no lexical repetition other than the verb. The target blocks alternated with filler blocks with an average length of 3.5 (range 2-5 items). In lists without verb repetition, the verb of the filler items was not repeated within one block either. In lists with verb repetition, the verb was repeated mostly between filler items within one block. Only for 10 % of the fillers items this was not the case, thus bringing in some extra variation. A full list of items presented to the participant consisted of approximately 59% transitive structures and 41% fillers. Fifty percent of the items were production items and 50% were comprehension items.

A full list of items (in the condition without or with verb repetition) contained the following elements. There were 20 items in each of the 16 conditions resulting from fully crossing the within-subject factors. Additionally, in the beginning of each of the 80 blocks of transitive structure items, there was one transitive structure item serving as a prime-only item. This increased the number of transitive structure items to 400. Each participant received 680 trials in total during a full lists of items (transitive and filler structures), which were distributed over two scanning sessions. In a full list of items presented to the participant, a certain action or a certain pair of actors could occur several times, but the combination of actors and action was unique. Every participant saw a different list of items.

Task and Procedure

The stimuli were presented in the following way. First, the verb was presented (in citation form, i.e. the infinitive). Then a photograph followed, accompanied by an auditory description during comprehension trials only. The presented verb was color-coded to let the participant know whether a 'comprehension photograph' or a 'production photograph' would follow. Green verbs preceded colored production photographs and gray verbs preceded black/white comprehension photographs (Figure 2).

Production. During production trials, the task was to describe the color-coded photographs overtly with a short sentence that should include (a conjugated form of) the presented verb. Participants were instructed to name the green actor before the red actor (stoplight paradigm: Menenti et al., 2011). There was no cue for the participants to start the descriptions; they could freely start whenever they were ready.

Comprehension. During comprehension trials, we used a sentence-picture matching paradigm (Clark & Chase, 1972): participants were presented with a photograph and an auditory description. The photographs were the grayscale version of the ones used in the production trials. This paradigm has been used extensively and a recent study supports that it is suitable for studying online situated language comprehension (Knoeferle, Urbach, & Kutas, 2011). By choosing situated paradigms for both production and comprehension trials, we maximize comparability and ensure that the difference between the two only lies in language processing. To have participants pay attention, we instructed them to listen carefully to the description of the black/white photographs and use the response box to indicate when this description was incorrect (the response hand was counterbalanced between participants). During 10% of the comprehension trials there was a mismatch between the description and the photographs. Only for those trials a response had to be given.

Participants completed a short practice block in the scanner before the actual experiment started. The experiment consisted of two runs of 45 minutes. Between the two runs the participants were subjected to an anatomical T1 scan and had a short break outside the MRI-scanner. Each trial consisted of the following events. First, the verb was presented for 500ms. After an ISI of 500-2500 ms, the photograph was presented for 2000 ms, whereafter the screen turned black. The photograph thus had a fixed presentation time during production as well as comprehension trials. In production trials, the participants started speaking during the presence of the photographs. In comprehension trials, the auditory sentence was presented after the photograph with an ISI of 0-1000 ms, enabling us to differentiate between the onset of the photograph and the auditory description in our analyses. The total trial duration of one trial was 7000 ms. Ten participants participated in both conditions of the between-subject factor Verb Repetition. They first completed the experiment with a list containing verb repetition and 18 months later they completed the experiment with a list containing no verb repetition.

The experimenter coded the participant's production responses online for correctness. Target trials were analyzed if during both prime and target trial (1) the correct structure was used, and (2) both actors were named accurately and the verb was used correctly.

fMRI Data Acquisition

Participants were scanned with a Siemens 3T Tim-Trio MRI-scanner, using a 12-channel surface coil. In order to acquire functional data we used parallel-acquired inhomogeneity-desensitized fMRI (Poser, Versluis, Hoogduin, & Norris, 2006). This is a multi-echo EPI sequence, in which images are acquired at multiple TE's following a single excitation (TR = 2.398s; each volume consisted of 31 slices of 3 mm thickness with slice-gap of 17 %; isotropic voxel size = 3.5x3.5x3 mm^3; field of view = 224 mm). The functional images were acquired at following TE's: TE_1 at 9.4 ms, TE_2 at 21.2 ms, TE_3 at 33 ms, TE_4 at 45 ms, and TE_5 at 56 ms, with echo spacing of 0.5 ms. This entails a broadened T_2* coverage, because T_2* mixes into the five echoes in a different way, and the estimate of T_2* is improved. Accelerated parallel imaging reduces image artifacts, hence is a suitable method to acquire data when participants are producing sentences in the scanner (causing motion and susceptibility artifacts). However, the number of slices did not allow acquisition of a full brain volume in most participants. We made sure that the entire temporal and frontal lobes were scanned because these were the regions where the fMRI adaptation effects of interest were expected. This meant that data from the superior posterior frontal lobe and the superior parietal lobe (that is, data from the top of the head) could not be obtained in several participants. A whole-brain high-resolution structural T1-weigthed MPRAGE sequence was performed to characterize participants' anatomy (TR = 2300 ms, TE = 3.03 ms, 192 slices with voxel size of 1 mm^3, FOV = 256), accelerated with GRAPPA parallel imaging.

Data Analysis

Preprocessing. fMRI data were preprocessed using SPM5 (Friston, Ashburner, Kiebel, Nichols, & Penny, 2007). The first 5 images were discarded to allow for T_1 equilibration. Then the five echoes of the remaining images were realigned to correct for motion artifacts. Estimation of the realignment parameters was done for one echo and then copied to the other echoes. The five echoes were combined into one image using a method designed to filter task-correlated motion out of the signal (Buur, Poser, & Norris, 2009). First, echoes two through five (i.e., TE_2, TE_3, TE_4 and TE_5) were combined using a weighting vector with weights depending on the measured differential contrast-to-noise ratio. The time course of an image acquired at a very short echo time (TE_1) was then used in a linear regression as a voxelwise regressor for the other image (i.e., the result of combining TE_2, TE_3, TE_4 and TE_5) in the same echo train acquired with high BOLD sensitivity. The resulting images were coregistered to the participants' anatomical volume, normalized to MNI space and spatially smoothed using a 3D isotropic Gaussian smoothing kernel (FWHM = 8mm).

Whole-Brain Analysis. We performed first- and second-level statistics using the general linear model framework of SPM5 (Friston et al., 2007). Our 2x2x2x2x2 design resulted in 32 conditions, hence 32 main regressors, for the statistical analysis of the fMRI data. We used an implicit baseline. In the first-level linear model, we modeled the individual onset times of the photograph (during production trials) or the auditory sentence description (during comprehension trials). We modeled the hemodynamic response function as related to these onsets and set the duration to zero. Separate regressors were included for verbs, photographs during comprehension trials, fillers items, items which were only primes, and incorrect responses. The events of the model were convolved with the canonical hemodynamic response function provided by SPM5. The temporal derivatives were included in the model as well. Furthermore, six motion parameters (realignment parameters: translation along, and rotation around, the x, y and z axes) and two parameters which correct for global intensity fluctuations (compartment signal parameters: white matter and cerebral spinal fluid; Verhagen, Dijkerman, Grol, & Toni, 2008) were added as regressors. For the second-level random-effects analysis we used the beta-images of the 32 main regressors.

Region of Interest (ROI) Analysis. Menenti et al. (2011) suggests that activations related to syntactic processing in comprehension and in production are centered around MNI coordinates [-52 10 22] in left IFG (BA 44) and MNI coordinates [-56 -44 4] in left MTG (BA 21). We used an 8-mm sphere around both MNI coordinates. Average time courses were calculated using Marsbar (http://marsbar.sourceforge.net/). For the ROI analysis at the second level we carried out a repeated-measures ANOVA on the subject contrast values using SPSS; independent variables were Region (LIFG vs. LMTG), Syntactic Repetition (novel syntax vs. repeated syntax), Target Structure (active vs. passive voice), modality of the prime (listening vs. speaking),modality of the target (comprehension/listening vs. production/speaking) and Verb Repetition (novel verb vs. repeated verb).

Results

Whole-Brain Analysis

We report clusters with voxel-level uncorrected $P < .001$. The cluster size is used as the test statistic with the criterion set at $P < 0.05$ corrected for multiple non-independent comparisons.

The following regions showed a repetition suppression effect for repeated versus novel syntactic structures (Figure 3A): the left inferior frontal gyrus extending into left insula, and the left precentral gyrus (BA 44/45/47/6), the bilateral supplementary motor area (BA 32), and the bilateral parietal regions (BA 40: inferior parietal and BA 7: precuneus). In addition, we note that there was repetition suppression for repeated versus novel syntactic structures in left middle temporal gyrus (BA 22) (peak coordinates [-52 -38 2]) with voxel-level uncorrected $P < .001$, but this cluster did not reach significance at $P < 0.05$ corrected for multiple non-independent comparisons.

The following regions showed a repetition suppression effect for repeated versus novel verbs (Figure 3B): the left inferior frontal gyrus extending into left precentral gyrus (BA 44/45), the left middle temporal gyrus (BA 21), and the left inferior parietal regions (BA 40).

There were no repetition enhancement effects. There were no regions showing an interaction between the effect of syntactic repetition and the effect of verb repetition. Also, we did not find any regions showing a three-way interaction between syntactic repetition, verb repetition and any of the other factors we manipulated.

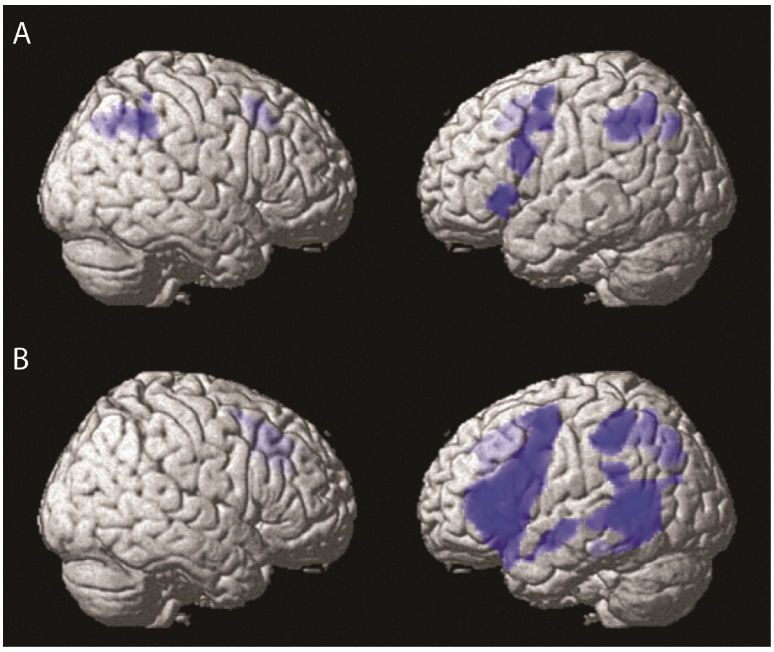

Figure 3. Whole brain results. (A) The fMRI adaptation effects for syntax repetition. In left inferior frontal regions and bilateral supplementary motor area and parietal regions (inferior parietal and precuneus) there was a repetition suppression effect for repeated compared to novel syntactic structures (see Table 1). (B) The fMRI adaptation effects for verb repetition. In left inferior frontal, middle temporal and inferior parietal regions there was a repetition suppression effect for repeated compared to novel verbs (see Table 2).

Table 1

Anatomical label	BA	global and local maxima			cluster-level		voxel-level
		x	y	z	K	P(corr)	Z
Main effect syntax repetition (no syntactic repetition > syntactic repetition)							
L inf parietal	40	-42	-42	38	897	<.001	5.97
L inf parietal	40	-32	-48	36			5.14
L inf parietal	40	-36	-48	38			5.11
R inf parietal	40	36	-52	40	506	<.001	4.99
R inf parietal	40	46	-46	42			3.95
R inf parietal	40	44	-44	54			3.30
L precuneus	7	-8	-70	40	358	.001	4.81
R precuneus	7	10	-70	40			3.97
R precuneus	7	12	-66	38			3.93
L insula	13/15	-28	24	0	479	<.001	4.78
L insula	13/15	-38	22	0			4.06
L inf frontal (pars orbitalis)	38	-52	24	-2			3.72

Table 1 continued

Anatomical label	BA	global and local maxima			cluster-level		voxel-level
		x	y	z	K	P(corr)	Z
L precentral	6	-36	0	42	839	<.001	4.71
L inf frontal (p. triangularis)	44	-42	12	26			4.11
L inf frontal (p. opercularis)	44	-52	14	18			4.11
R mid cingulum	23	2	-26	26	180	.028	4.41
R mid cingulum	23	4	-22	28			4.30
L supp motor area	32	-2	14	54	286	.003	4.13
R supp motor area	32	6	18	48			1.09
L supp motor area	32	-4	16	44			3.65
Main effect verb repetition (no verb repetition > verb repetition)							
L mid temporal	21	-58	-46	2	2588	<.001	7.55
L mid temporal	21	-60	-52	6			7.51
L mid temporal	21	-44	-50	14			5.36
L precentral	44	-48	6	30	5851	<.001	7.54
L inf frontal (p. triangularis)	45	-50	34	12			6.30
L inf frontal (p. triangularis)	45	-42	30	2			5.85
L inf parietal	40	-46	-42	50	1536	<.001	5.17
L inf parietal	40	-42	-38	40			4.63
L inf parietal	40	-56	-36	46			4.55
L mid temporal	21	-56	-4	-14	296	.003	4.55
L mid/ sup temporal	22	-56	-12	-6			4.17
L mid temporal	21	-54	8	-22			3.30
Interaction syntax repetition x verb repetition							
no significant clusters							

Note: Listed are the MNI-coordinates for three local maxima for each significant cluster in the relevant comparisons (*P*<.05 corrected cluster-level, threshold *P*<.001 uncorrected voxel-wise). Anatomical labels are derived from the Automated Anatomical Labeling map (Tzourio-Mazoyer et al., 2002) and from Brodmann's atlas.

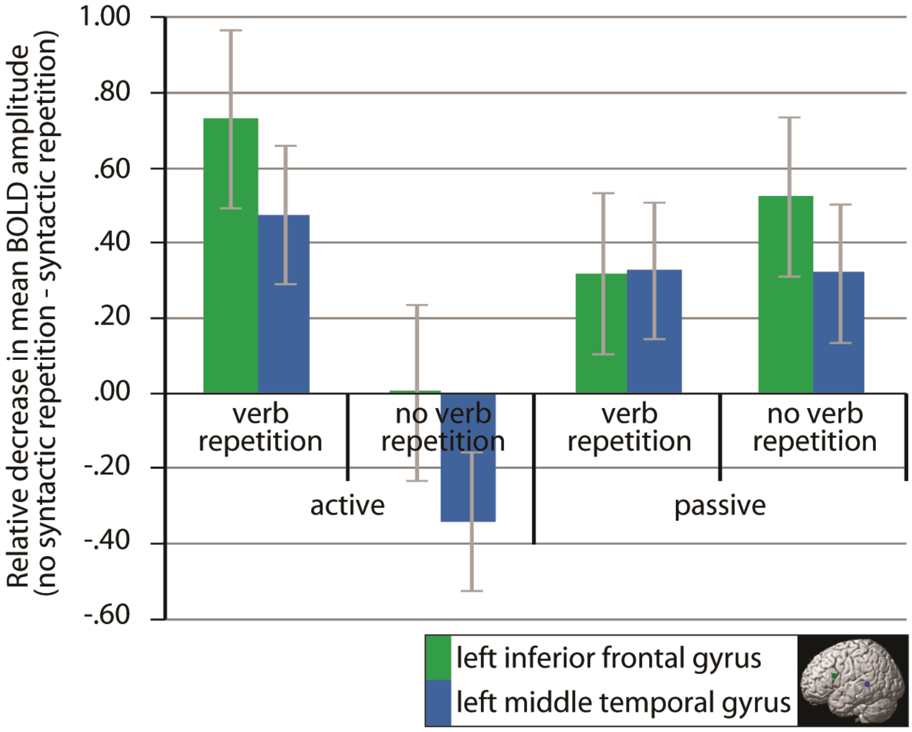

Figure 4. ROI results. The repetition suppression effect for sentences with a repeated syntactic structure (i.e. sentences with novel syntax minus sentences with repeated syntax), in function of whether the sentence was active or passive, and whether the verb was repeated between consecutive sentences or not. These repetition suppression effects are depicted separately for two ROI's: the left inferior frontal gyus and the left middle temporal gyrus.

ROI analysis

To maximize detection power, we also investigated possible interactions between syntactic repetition and verb repetition in ROI analysis. The sensitivity on the whole-brain level may have been insufficient to detect interactions with a between-group factor. In ROI analyses, we can search for potential interactions between syntactic repetition and verb repetition at the highest possible statistical sensitivity. We performed ROI analysis in left IFG and left MTG (clusters based on Menenti et al., 2011).

An ROI analysis revealed that there was a main effect of the between-subject factor Verb Repetition ($F_{1,46} = 51.1$, $P < .001$): the ROIs were less activated when the verb was repeated than when the verb was novel. The ROIs were also less activated by sentences with repeated syntactic voice than by sentences with novel syntactic voice ($F_{1,46} = 12.4$, $P < .001$). There was less activation for active than for passive sentences ($F_{1,46} = 45.0$, $P < .001$). Furthermore, we obtained main effects of prime modality ($F_{1,46} = 18.4$, $P < .001$) and target modality ($F_{1,46} = 77.6$, $P < .001$), indicating that the ROIs were less activated during comprehension trials.

Additionally, there was a two-way interaction between syntactic repetition and verb repetition ($F_{1,46} = 4.02$, $P < .05$) and a three-way interaction between syntactic repetition, target structure and verb repetition ($F_{1,46}$ = 5.90, $P < .019$; Figure 4). Follow-up contrasts showed that under conditions of verb repetition, there was a significant effect of syntactic repetition ($F_{1,23}$ = 15.2, $P < .001$) which did not interact with the target structure ($F_{1,23}$ = 1.02, $P > .3$). Under conditions without verb repetition, we found no overall effect of syntactic repetition ($F_{1,23}$ = 1.16, $P > .3$); instead, the effect of syntactic repetition appeared to depend on the target structure ($F_{1,23}$ = 6.68, $P < .017$). More specifically, under conditions without verb repetition, there were syntactic adaptation effects for passive ($F_{1,23}$ = 8.44, $P < .008$), but not for active sentences ($F_{1,23}$ = .86, $P > .3$). Processing modality of the prime or the target did not affect the strength of syntactic adaptation effects.[1] None of these effects interacted with whether the ROI was LIFG or LMTG.

In order to explore whether differences between participants might contribute to the differences between conditions with verb repetition and conditions without verb repetition, we investigated whether any of the effects under conditions without verb repetition interacted with a factor Participants with 2 levels: participants subjected to conditions without verb repetition only vs. participants subjected to conditions with as well as without verb repetition. There were no such interactions.

Discussion

In the present study we investigated whether the neuronal activity in brain regions subserving syntactic processing reveals lexically boosted syntactic priming effects. We focused on syntactic priming of sentences in active and passive voice. The verb and/or the syntactic voice of two successive sentences was either repeated or novel. Whole-brain analysis revealed that there was repetition suppression in the left IFG and left MTG for sentences with a repeated compared to novel syntax and for sentences with a repeated compared to a novel verb (note that the effect of syntactic repetition in the left MTG did not reach significance at cluster-level corrected for multiple comparisons ($P < .05$), however). Whole-brain analysis did not reveal any interactions between syntactic repetition and verb repetition. To maximize the detection power, we also investigated possible interactions between syntactic repetition and verb repetition in an ROI analysis. The ROI analysis in the left IFG and left MTG revealed the same pattern of results in both regions. We observed a lexical boost of fMRI adaptation to syntactic repetition for sentences in active voice: there was fMRI adaptation to syntactic repetition when actives had a repeated verb, but no fMRI adaptation to syntactic repetition when actives had a novel verb. For sentences in passive voice, there was no lexical boost: there was fMRI

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[1] In Segaert et al. (2011) we showed that, under conditions of verb repetition, there was no interaction between the effect of syntactic repetition (repeated vs. novel syntax of prime and target sentence) and the effect of modality repetition (repeated vs. novel modality of prime and target sentence). The finding that syntactic repetition facilitates syntactic processing in the brain within and across processing modalities to the same extent indicates that the same neurobiological system subserves syntactic processing in speaking and listening. The current study constitutes a replication/verification of this finding: Under conditions without verb repetition, there is no interaction between syntactic repetition and modality repetition ($F_{1,23}$ = .82, $P > .3$). Also, there is no interaction between syntactic repetition, target structure and modality repetition ($F_{1,23}$ = .04, $P > .8$).

adaptation to syntactic repetition both for passives with a repeated verb and for passives with a novel verb. The processing modality of the sentences (speaking vs. listening) did not affect these results.

Our tentative interpretation of the results is as follows. Sentences in active voice are much more frequently used than, and are strongly preferred over, sentences in passive voice (Segaert, Menenti, Weber, & Hagoort, 2011). This may have lead to a "floor effect": priming of a sentence in active voice did not reduce neuronal activity to an extent that could be picked up by the BOLD measurements. Only when syntactic priming of the active voice construction was helped by verb repetition, repetition suppression for primed actives became observable. On the other hand, for primed sentences in passives voice, repetition suppression was observed also in the absence of verb repetition. Because passive sentences are much less frequent, a priming benefit in the form of a repetition suppression effect could show up more readily, even in the absence of verb repetition.

Another property of passive voice sentences that may cause them to be more liable to syntactic priming than active voice sentences is the fact that they share syntactically important words other than the head verb. The words 'are by' in English and 'worden door' in Dutch are repeated obligatorily. The syntactic skeleton of a passives sentence in English is:

'[…] be [participle] by […]'

and in Dutch, it is:

'[…] worden door[…] [participle]'.

Hence, the syntactic priming effect we observed for passives may, at least partially, be attributed to repetition of lexical items other than the main verb. Repetition of content words other than the head of a phrase has been found to lead to a lexical boost of behavioral syntactic priming effects (Raffray, Scheepers, & Myachykov, 2009).

However, why did repetition of the main verb (the participle) in passives not increase the repetition suppression effect any further? A possible answer has to do with an important property of linear (sequence) order in Dutch: As indicated in the syntactic skeleton, the main verb—the participle—is mentioned in Dutch *after* the two protagonists involved in the depicted action. Hence, the participants could have postponed planning the main verb until *after* having processed the descriptions of the protagonists. As is well-known, sentence processing often proceeds incrementally (Kempen & Hoenkamp, 1982, 1987; Levelt, 1989). By postponing, in passive sentences, the planning of the description of the action, the participants could, in effect, spread out processing load over a longer time interval, compared to planning active sentences, where the main verb often must have been planned early in the sentence. Note that this explanation presupposes the assumption that dealing with the verb contributes more to the activation elicited by syntactic processing than dealing with the noun phrases governed by the verb. Actually, there is independent fMRI evidence that early placement of main verbs increases the BOLD response in comparison to later placement. Den Ouden et al. (2008) found that Dutch active-voice clauses with Subject-Verb-Object order elicited larger BOLD responses in left middle to superior frontal regions than actives with Subject-Object-Verb order.[2]

Our tentative explanation of the differential effect of the lexical boost for actives versus passives could be tested by repeating the present experiment with slightly different Dutch stimulus materials where the active sentences embody a perfectum construction, with the main verbs realized as past-participles governed by the active auxiliary *heeft* ('has'), e.g. *De jongen heeft het meisje gewurgd [The boy has strangled the girl].* In active sentences of this type, the verb is placed after both protagonists in the transitive event, just like in passive sentences, e.g. *Het meisje werd door de jongen gewurgd [The girl was strangled by the boy]*).

The results reported above confirm previous findings on the functional contribution of the lIFG and lMTG (Menenti et al., 2011; Segaert, Menenti, Weber, Petersson, et al., 2011; Snijders et al., 2009): both regions are involved in syntactic processing in production and comprehension.

Importantly, our set of findings on the presence versus absence of a lexical boost of syntactic priming were unaffected by whether the processing modality of the sentences was production or comprehension. In the behavioral literature, findings of syntactic priming in comprehension seem to be almost completely lexically dependent (Arai et al., 2007; Branigan et al., 2005; Tooley et al., 2009; Traxler & Tooley, 2007), whereas syntactic priming in production is also observed in the absence of lexical repetition (Branigan et al., 2000; Hartsuiker et al., 2008; Pickering & Branigan, 1998). Measurement of neuronal activity allows for a direct comparison between the two processing modalities, while comparable behavioral measures of production and comprehension are hard to find. The magnitude of the verb repetition effect at the neuronal level was the same in our comprehension and production tasks. This finding suggests that the behavioral signatures of syntactic priming may reflect different processing aspects than the hemodynamic responses in lIFG and lMTG.

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[2] den Ouden et al. (2008) interpret the increased BOLD-response for sentences with Subject-Verb-Object order compared to Subject-Object-Verb order as evidence for a syntactic transformation that moves the finite verb from the unmarked/default position in to the marked verb-second position.

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Chapter 6

Remaining mysteries.
Short versus long term priming of syntax and verbs – behavioural and neuronal effects

Speakers have a preference for recently used syntactic structures, a phenomenon called syntactic priming. Different mechanisms have been proposed to drive syntactic priming: implicit learning of mapping abstract syntactic frames to a message on the one hand and residual activation of syntactic information represented in the mental lexicon on the other. Using neuroimaging we investigated the possibility of a multifactorial account of syntactic priming: different syntactic priming mechanisms may be reflected in the neuronal activity of different regions in the brain and/or with different time courses. In this fMRI study, participants gave overt descriptions of pictures using active or passive transitive sentences. Subsequent sentences were independently manipulated for syntactic repetition, verb repetition and the longevity of priming. We investigated whether there were brain regions showing an interaction between the effect of syntactic repetition and the effect of verb repetition – this would provide support for the residual activation account. We also investigated whether there were brain regions showing an interaction between the effect of syntactic repetition and the longevity of priming – this would provide support for the implicit learning account. Surprisingly, we did not find any effects of syntactic repetition in regions commonly associated with syntactic processing, like the left IFG and left MTG. These puzzling findings make it difficult to draw any definite conclusions about the mechanisms driving syntactic priming.

Introduction

In this chapter we will focus on syntactic processing during language production. Speakers reuse syntactic structures across utterances, a phenomenon called *syntactic priming* (Bock, 1986). Syntactic priming refers to the facilitated processing of a syntactic structure when it is the same as the syntactic structure of a preceding sentence. Behavioural indicators of this facilitation are an increased likelihood to produce the same syntactic structure and/or faster production of the same structure (Segaert, Menenti, Weber, & Hagoort, 2011). The present study is designed to investigate how different aspects of syntactic priming in language production are manifested in the brain and how this relates to the facilitation observed at the behavioural level. More specifically, we will investigate the influence of short versus long term syntactic priming as well as the influence on syntactic priming of verb repetition, at the behavioural and at the neuronal level.

The mechanism behind syntactic priming

The mechanism behind syntactic priming is a matter of debate. There are two influential accounts, each with a different view on how syntactic structures are encoded: an error-based implicit learning account (Chang, Dell, & Bock, 2006; Chang, Dell, Bock, & Griffin, 2000) and a lexicalist residual activation account (Cleland & Pickering, 2003; Pickering & Branigan, 1998). These two accounts differ in their assumptions about the mechanism responsible for syntactic priming and make different predictions about its effects.

According to the implicit learning account, the use of syntactic procedures entails learning (Chang et al., 2006; Chang et al., 2000). Language users continuously learn mappings between the representation of a message (e.g. a message specifying an agent operating on a patient) and the representation of a syntactic structure (e.g. a passive syntactic structure). According to this account, sentence structures are assembled through the construction of abstract syntactic frames into which lemmas (frames representing information about words) are afterwards inserted. In other words, when a speaker uses a syntactic structure, he or she gains experience in expressing a message with that particular syntactic structure. The consequence of this adjustment is that a previously used syntactic structure is more likely to be used again. Adjustments due to implicit learning are relatively permanent, so the effects are predicted to be long lasting (Chang et al., 2006; Chang et al., 2000). Furthermore, since the process assumed to be responsible for syntactic priming takes place outside the mental lexicon, syntactic priming effects should not be boosted by lexical repetition.

The residual activation account (Cleland & Pickering, 2003; Pickering & Branigan, 1998) on the other hand highlights the role of lexical representations in selecting syntactic structures. This account proposes that each verb is represented in the mental lexicon with connections to frames specifying in which syntactic alternatives the verb can be used. In the case of a transitive verb like 'strangle', the verb is connected to a frame specifying that it can be used in an active structure and another frame specifying that it can be used in a passive structure. When a syntactic frame (e.g. a frame specifying the passive structure) is recently activated, residual activation will promote repeated selection of this frame and thus encourage speakers to reuse the syntactic structure. For a transitive sentence with a repeated verb, not only residual activation in a syntactic frame but also a strengthened link between this frame and the verb will affect syntactic processing. So when the head of the construction, i.e. for transitive sentences the verb, is repeated, syntactic priming effects should be boosted. However, residual activation of information in memory is subject to decay and the activation of a syntactic rule or a certain verb will not persist permanently. It is an open question how activation dissipates: this may be purely as a function of time or activation may decay when other syntactic structures are activated (Pickering, Branigan, Cleland, & Stewart, 2000). Either way, according to the residual activation account long lasting priming effects should not occur.

In Chapter 4 and 5 we discussed a computationally explicit account of syntactic processing called Unification-Space (Vosse & Kempen, 2000, 2009). For every incoming word a "lexical frame" is retrieved from the Mental Lexicon - an elementary syntactic tree that specifies the possible syntactic environment of a given word. Every retrieved lexical frame is entered into the Unification Space - the workspace where all retrieved lexical frames are unified into a syntactic tree spanning the entire input sentence. The unification process causes the lexical frames to be linked or bound together in such a way that agreement and word order constraints are met. Given that Unification-Space is a lexicalist grammar formalism, it bears similarity to the residual activation account in terms of how syntactic information is represented. However, in terms of the processing mechanism we consider Unification-Space to be more similar to the implicit learning account. In the framework of Unification-Space, syntactic priming can be viewed as priming of the unification process. This bears similarity to implicitly learning how to express a certain message with a particular syntactic structure.

Evidence for the implicit learning and residual activation account of syntactic priming

The two accounts of syntactic processing we discussed above make contradicting predictions about the existence of a lexical boost and the longevity of syntactic priming. While the implicit learning account predicts the absence of the former and presence of the latter, the residual activation account predicts the presence of the former and absence of the latter.

Numerous behavioural studies have investigated either one of these aspects. Results from studies investigating verb repetition as potential lexical enhancer of syntactic priming effects largely favour a lexicalist residual activation account: syntactic priming effects on behavioural response tendencies are boosted when the verb is repeated (Branigan, Pickering, & Cleland, 2000; Pickering & Branigan, 1998; Segaert et al., 2011). However, the only study so far that investigated the effect of verb repetition on syntactic priming effects in response latencies revealed that these were not affected by verb repetition (see Chapter 2: Segaert et al., 2011). Results from behavioural studies investigating the longevity of syntactic priming effects on the other hand seem to favour the implicit learning account: several studies measuring response tendencies do find evidence for long term priming persisting over time (Boyland & Anderson, 1998; Branigan, Pickering, Stewart, & McLean, 2000) or over intervening trials (Bock, Dell, Chang, & Onishi, 2007; Bock & Griffin, 2000; Branigan, Pickering, Stewart, et al., 2000). No studies have investigated whether syntactic priming effects on response latencies are long lasting.

Each of the two accounts can only explain parts of the empirical evidence from behavioural studies, but neither can account for all the evidence. This has led some to propose that multiple mechanisms are underlying syntactic priming effects (Bock & Griffin, 2000; Chang et al., 2006; Ferreira & Bock, 2006). A multifactorial account is supported by two studies showing syntactic priming to be long lasting while only immediate syntactic priming effects are boosted by lexical repetition of the verb (Hartsuiker, Bernolet, Schoonbaert, Speybroeck, & Vanderelst, 2008; Konopka & Bock, 2005).

So far only one neuroimaging study has investigated the influence of verb repetition on syntactic repetition effects in the brain (see chapter 5: Segaert, Kempen, Petersson, & Hagoort, submitted). The results of this study revealed a complex pattern of results: syntactic repetition effects for actives sentences were boosted by verb repetition but syntactic repetition effects for passive sentences were not. No neuroimaging study to date has investigated the longevity of neuronal syntactic priming effects. Also, there have not been any studies that have investigated whether, similarly to the lexical boost of behavioural syntactic priming effects (Hartsuiker et al., 2008; Konopka & Bock, 2005), a lexical boost of neuronal syntactic repetition effects is only short lasting.

With the aim to increase our understanding of the lexical boost of syntactic priming and on the influence of long term priming, we investigated this in an fMRI study. This could give us the opportunity to elucidate and separate different mechanisms driving syntactic priming. By examining the neuronal activity of different regions in the brain and/or with different time courses, we could potentially disentangle the workings of qualitatively different syntactic priming mechanisms. We may be able to observe the implicit learning mechanism reflected in brain regions showing long term syntactic priming effects independent of lexical repetition. The residual activation mechanism may be reflected in other regions, showing only immediate syntactic priming effects that are boosted by lexical repetition. Finally, it is possible that we may see a combination of both.

Syntactic Processing in the Brain

Previous findings support the involvement of a distributed network of regions in syntactic processing. For syntactic processing in production these regions include Brodmann's areas (BA) 44/45 of the left inferior frontal gyrus (Haller, Radue, Erb, Grodd, & Kircher, 2005; Menenti, Segaert, & Hagoort, submitted; Segaert, Menenti, Weber, Petersson, & Hagoort, 2011), BA 21/37 of left temporal gyri (Menenti et al., submitted; Segaert et al., 2011), left BA 6/44 of the anterior Rolandic operculum (Indefrey et al., 2001; Indefrey, Hellwig, Herzog, Seitz, & Hagoort, 2004), left medial frontal gyrus (Haller et al., 2005), left superior parietal lobe (Haller et al., 2005; Menenti et al., submitted) and right insula (Haller et al., 2005).

The present study

In the present study we investigate the behavioural effects as well as the neuronal substrate of syntactic priming of transitive sentences in language production. We will investigate the behavioural effect of syntactic priming in measurements of the response latencies (the speech onsets of sentence production). To investigate the neuronal substrate of syntactic priming, we will make use of an fMRI adaptation paradigm. fMRI adaptation is a phenomenon whereby the BOLD-response in regions sensitive to a stimulus property, e.g. syntax, is reduced or enhanced when this stimulus property is repeated (Grill-Spector, Henson, & Martin, 2006; Henson, 2003; Segaert, Weber, de Lange, Petersson, & Hagoort, submitted). To be able to relate behavioral effects to effects in the brain, we will investigate the neuronal substrate of syntactic priming for active and passive transitive sentences separately. Behavioural syntactic priming effects have been found to differ for active and passive transitive sentences (see Chapter 2: Segaert et al., 2011).

We will manipulate syntactic repetition simultaneously with verb repetition and the number of intervening trials between the prime and the target. The aim of the manipulation of verb repetition is to investigate the role of the verb as a lexical enhancer of syntactic priming effects. The manipulation of the number of intervening trials between prime and target aims to investigate whether the effects of short term (over no intervening trials) and long term (over intervening trials) priming are the same.

Our neuroimaging approach could potentially enable us to disentangle the contribution of qualitatively different syntactic priming mechanisms possibly working at the same time in different regions of the brain or with different time courses. If implicit learning drives syntactic priming, then we should see brain regions showing long term syntactic priming effects independent of lexical repetition. If residual activation drives syntactic priming, we should see brain regions showing only immediate syntactic priming effects that are boosted by lexical repetition. We may also see a combination of both.

Methods

Participants

Twenty-four right-handed native Dutch speakers without neurological or language impairments and with normal or corrected to normal vision (eight male; mean age 20.5 years ± 1.4) participated in the experiment. All participants were attending university in the Netherlands. All participants gave written informed consent prior to the experiment and were compensated for their participation.

Materials

The materials used in this study are identical to the materials used in Menenti, Segaert and Hagoort (submitted). The stimulus set consisted of 962 pictures in total. Four hundred thirty-two pictures elicited transitive sentences and were used for the target trials. These pictures depicted an agent and a patient (a man and a woman or a boy and a girl) performing a transitive action such as *kissing, helping, strangling* (see Figure 1 for examples and see appendix 2.1 for a full list of the 36 transitive actions depicted). Each event was enacted in the pictures by three couples (2 x man/woman; 1 x boy/girl), each of these once with the male actor as agent and once with the female actor as agent. Of each transitive picture there were two color-coded versions which elicited either active or passive sentence descriptions (participants were instructed to describe these pictures naming the green actor before the red actor – see task description). There was an active version with a green agent and a red patient and a passive version with a red agent and a green patient. The position of the agent (left or right) was randomized.

Additionally, there was a filler set of 530 pictures (see Figure 1 for examples). Four-hundred fifty-four pictures (i.e. 86 % of the fillers) elicited intransitive sentences. These pictures depicted one agent (colored either green or red) performing an intransitive action such as *singing* and *running.* The agents were sometimes famous people, animals or people that could be named by their profession. Seventy-six pictures (14% of the fillers) elicited locative sentences. These pictures depicted two objects and actions

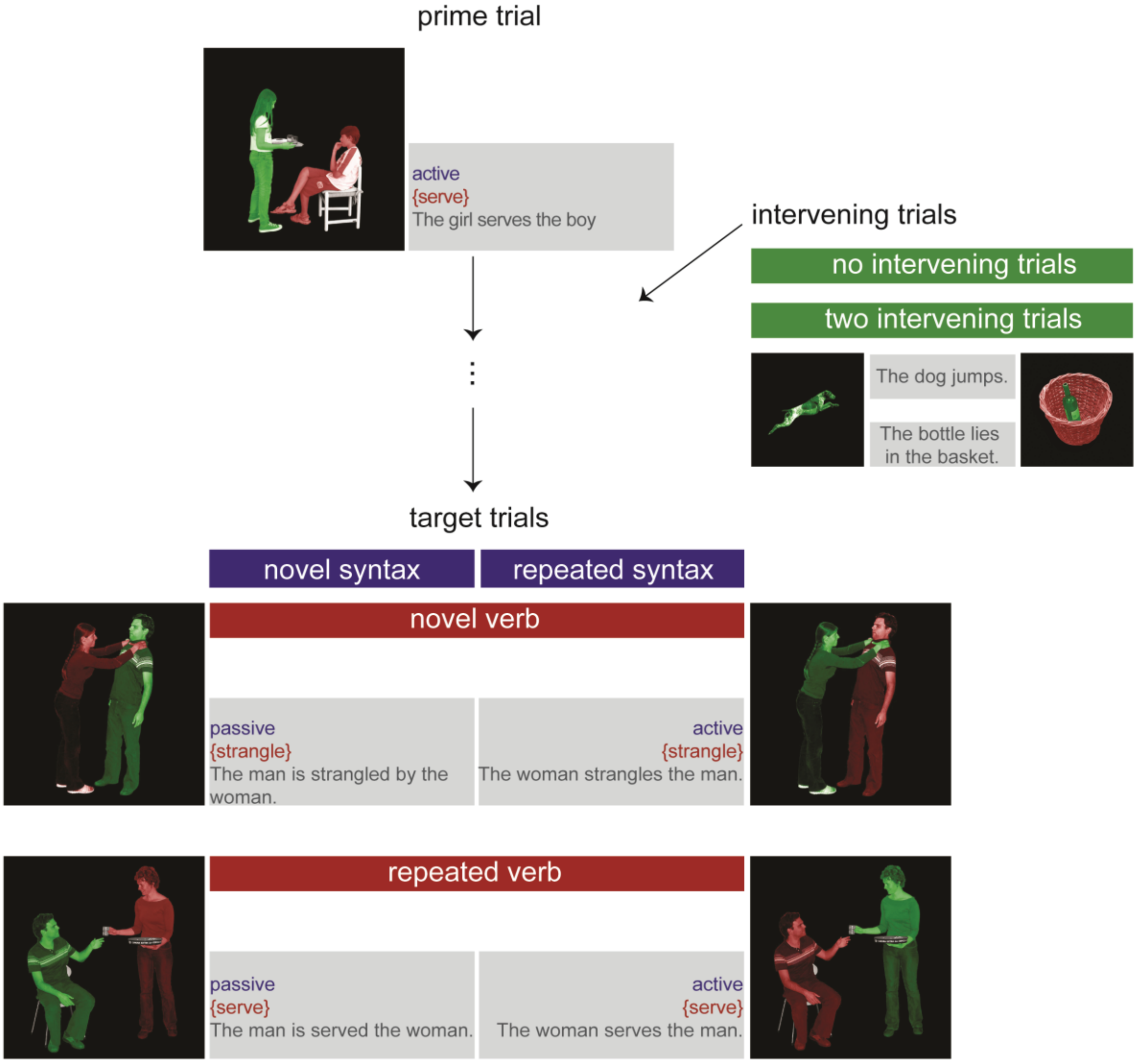

Figure 1. Participants were instructed to describe pictures with short sentences naming the green actor before the red one. In this way, for transitive events participants were forced to produce an active or a passive sentence. Furthermore, subsequent transitive sentences (a prime and a target) were independently manipulated for syntax repetition (novel versus repeated syntax), verb repetition (novel versus repeated verb) and the number of intervening trials (zero versus two intervening trials).

such as *standing* and *lying*. The objects were color-coded, one green and one red, to elicit a locative state (‘*The ball lies on the table*’) or a frontal locative (‘*On the table lies a ball*’) sentence. These filler items provoked variability in syntactic structures as well as lexical items that participants produced during the experiment.

We pretested the materials to establish whether the depicted actions were clear and to measure which verb was most commonly used to describe the action. During the actual experiment this verb was presented preceding the pictures.

Experimental design

We used a 2 x 2 x 2 x 2 design with the factors Syntactic Repetition (novel vs. repeated syntax between prime and target), Verb Repetition (novel vs. repeated verb between prime and target), Intervening Trials (no intervening trials vs. two intervening trials between prime and target) and Target Structure (active vs. passive target). This resulted in sixteen conditions. The design (the 8 conditions resulting from crossing the first 3 factors, thus, leaving out the factor target structure) is illustrated in Fig. 1.

We used a running priming paradigm where each target item also served as the prime sentence for the next target item (Figure 2). The conditions followed each other in a random order that was different for every participant, with two constraints on the order of conditions. The first constraint was that no condition was repeated twice in a row. The second constraint was that a target item with adults was always followed by a target item with children and vice versa, so that when the verb was repeated there was no lexical repetition other than the verb. Each picture could occur only once in the experiment and every participant saw a different list of items. The filler items for the intervening trials were chosen randomly from all the available filler items.

There were 31 target items in each of the conditions that resulted from crossing syntactic repetition, verb repetition and the number of intervening trials. These target items could be active or passive, this was determined randomly for each target item. Each participant received 504 trials in total. Half of these were pictures eliciting transitives, the other half were pictures eliciting locatives or intransitives. The trials were divided over two scanning sessions.

Task and procedure

The task was to describe the pictures overtly with a short sentence using the presented verb. Participants were instructed to name the green actor before the red actor (stoplight paradigm: Menenti, Gierhan, Segaert, & Hagoort, 2011).

Participants completed a short practice block in the scanner before the actual experiment started. The experiment consisted of two runs of 40 minutes. Between the two runs the participants underwent an anatomical T1 scan and a short break outside the MRI-scanner. Each trial consisted of the following events: first, the verb was presented for 500ms. After an ISI of 500-1500ms the picture was presented for 2000ms. After another ISI of 4000- 7000ms the next trial started.

The experimenter coded the participants’ responses online for correctness and prevoicing. Target trials were considered for analysis if during both prime and target trial 1) the correct structure was used and 2) both actors were named accurately and the verb was used correctly.

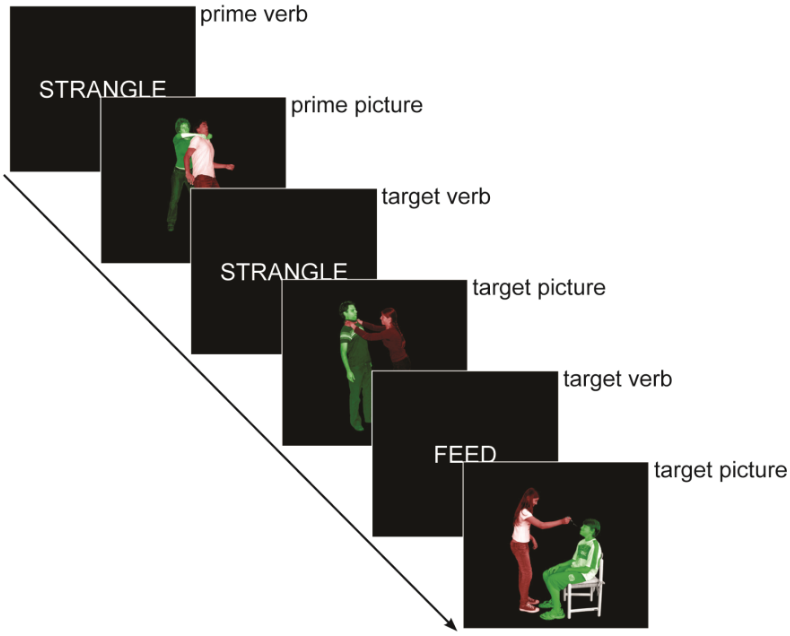

Figure 2. Overview of the priming paradigm (the arrow represents time).

Data acquisition

Participants' picture descriptions were recorded in order to extract the speech onset latencies (response latencies). Participants were scanned with a Siemens 3T Tim-Trio MRI-scanner, using a 12-channel surface coil. To acquire functional data we used parallel-acquired inhomogeneity-desensitized fMRI (Poser, Versluis, Hoogduin, & Norris, 2006). This is a multi-echo EPI sequence, in which images are acquired at multiple TE's following a single excitation (TR = 2.398s; each volume consisted of 31 slices of 3 mm thickness with slice-gap of 17 %; isotropic voxel size = 3.5x3.5x3 mm^3; field of view = 224 mm). The functional images were acquired at following TE's: TE$_1$ at 9.4 ms, TE$_2$ at 21.2 ms, TE$_3$ at 33 ms, TE$_4$ at 45 ms, and TE$_5$ at 56 ms, with echo spacing of 0.5 ms. This entails a broadened T$_2$* coverage, because T$_2$* mixes into the five echoes in a different way, and the estimate of T$_2$* is improved. Accelerated parallel imaging reduces image artefacts and thus is a good method to acquire data when participants are producing sentences in the scanner (causing motion and susceptibility artefacts). However, the number of slices did not allow acquisition of a full brain volume in most participants. We made sure that the entire temporal and frontal lobes were scanned because these were the regions where the fMRI adaptation effects of interest were expected. This meant that data from the superior posterior frontal lobe and the superior parietal lobe (thus data from the top of the head) were not acquired in several participants. A whole-brain high resolution structural T1-weigthed MPRAGE sequence was performed to characterize participants' anatomy (TR = 2300 ms, TE = 3.03 ms, 192 slices with voxel size of 1 mm^3, FOV = 256), accelerated with GRAPPA parallel imaging.

Data analysis of the behavioural data

In our study, we manipulated whether participants produced active or passive sentences by using the stop-light task. We did not allow participants to choose the syntactic structure they produced, in order to have enough trials during which passive sentences were produced. Therefore, we could only measure the behavioural syntactic priming effects on response latencies (the speech onsets of sentence production), not on the response tendencies.

Target trials for which an incorrect behavioural response was made, were excluded from the analysis. The speech recordings of participants' behavioural responses were preprocessed to separate the scanner sound from participants' speech. The recordings were bandpass filtered between 250 and 4000 Hz and smoothed with a width half the sampling rate. From this we extracted the speech onset and determined the response latencies (the time between the picture appearing on the screen and the speech onset of the sentence).

The response latencies were analysed in a repeated measures ANOVA using SPSS, with the factors syntactic repetition (novel/repeated), verb repetition (novel/repeated), target structure (active/passive) and intervening trials (no intervening trials/two intervening trials).

Data analysis of the fMRI data

Preprocessing. fMRI data were preprocessed using SPM5 (Friston, Ashburner, Kiebel, Nichols, & Penny, 2007). The first 5 images were discarded to allow for T_1 equilibration. Then the five echoes of the remaining images were realigned to correct for motion artefacts (estimation of the realignment parameters is done for one echo and then copied to the other echoes). The five echoes were combined into one image with a method designed to filter task-correlated motion out of the signal (Buur, Poser, & Norris, 2009). First, echo two to five (i.e., TE_2, TE_3, TE_4 and TE_5) were combined using a weighting vector with the weights depending on the measured differential contrast to noise ratio. The time course of an image acquired at a very short echo time (TE_1) was then used in a linear regression as a voxelwise regressor for the other image (i.e., the result of combining TE_2, TE_3, TE_4 and TE_5) in the same echo train acquired with high BOLD sensitivity. The resulting images were coregistered to the participants' anatomical volume, normalized to MNI space and spatially smoothed using a 3D isotropic Gaussian smoothing kernel (FWHM = 8mm).

Whole-Brain Analysis. Our 2 x 2 x 2 x 2 design resulted in 16 conditions and thus 16 main regressors for the statistical analysis of the fMRI data. In the 1st level general linear model we modeled the individual start time of the picture. Separate regressors were included in the first level model for the verbs, items which were only primes, fillers items and incorrect responses. The events of the model were convolved with the canonical hemodynamic response function provided by SPM5. Furthermore, six motion parameters (realignment parameters: translation along, and rotation around, the x, y and z axes) and two parameters which correct for global intensity fluctuations (compartment signal parameters: white matter and cerebral spinal fluid; Verhagen, Dijkerman, Grol, & Toni, 2008) were added as regressors. For the 2nd level random-effects analysis we used the beta-images of the 16 main regressors. The cluster size was used as the test statistic and only clusters significant at $P < 0.05$ corrected for multiple non-independent comparisons are reported. Local maxima are also reported for all clusters with their respective Z-values.

Region of Interest (ROI) Analysis. We performed ROI analyses in two regions previously found to be involved in syntactic processing in production: 1) in the left inferior frontal gyrus using an activation cluster with peak coordinates [-44 42 0] and cluster size 93 found by Menenti, Segaert and Hagoort (submitted); and 2) in the left middle temporal gyrus using an activation cluster with peak coordinates [-46 -60 -12] and cluster size 1175 found by Menenti et al. (submitted). Of these two clusters we calculated the average time courses using Marsbar (http://marsbar.sourceforge.net/). For the ROI analysis at the second level we carried out a repeated measures ANOVA with the factors syntactic repetition (novel/repeated), verb repetition (novel/repeated), target structure (active/passive) and intervening trials (no intervening trials/two intervening trials) on the subject contrast values using SPSS. We corrected for multiple comparisons by using a threshold for significance of $P = .05/2$.

Results

Behavioural results – response latencies

Before analyses 28% (1709 out of 5952) of trials had to be removed because 1) the response on the prime and/or target was incorrect (12% of the trials), 2) the speech onset could not be determined accurately (14% of the trials), or 3) response latencies were considered to be outliers (2% of the trials, i.e. when response latencies were not within 3 standard deviations from a participant's mean). Data loss was distributed evenly over the conditions.

There were main effects of syntactic repetition and of verb repetition: the response latencies were faster when the syntax was repeated ($F_{1,23}=6.61$, $P <.017$) and when the verb was repeated ($F_{1,23}=6.11$, $P <.021$). The response latencies tended to be faster when there were no intervening trials than when there were two ($F_{1,23}=2.95$, $P <.099$). Also, there was an overall effect of target structure: active transitive sentences were produced faster than passive transitive sentences ($F_{1,23}=18.33$, $P <.001$). Furthermore, there was a marginally significant interaction between syntactic repetition and target structure ($F_{1,23}=3.06$, $P <.093$). Planned comparisons revealed that there was an effect of syntactic repetition for actives ($F_{1,23}=9.95$, $P <.004$), but not for the passives ($F_{1,23}=.62$, $P >.4$) (Fig. 3).

Crucially, the syntactic priming effect was not affected by verb repetition or by the number of intervening trials. There was no interaction between syntactic repetition and verb repetition ($F_{1,23}=.40$, $P >.5$) or between syntactic repetition and the number of intervening trials ($F_{1,23}=.01$, $P >.9$) or between verb repetition, intervening trials and syntactic repetition ($F_{1,23}=1.27$, $P >.2$). Also there were no interactions with target structure (interaction between syntactic repetition, verb repetition and target structure: $F_{1,23}=1.28$, $P >.2$; between syntactic repetition, the number of intervening trials and target structure: $F_{1,23}=.02$, $P >.9$; between syntactic repetition, verb repetition, intervening trials and target structure: $F_{1,23}=.01$, $P >.6$).

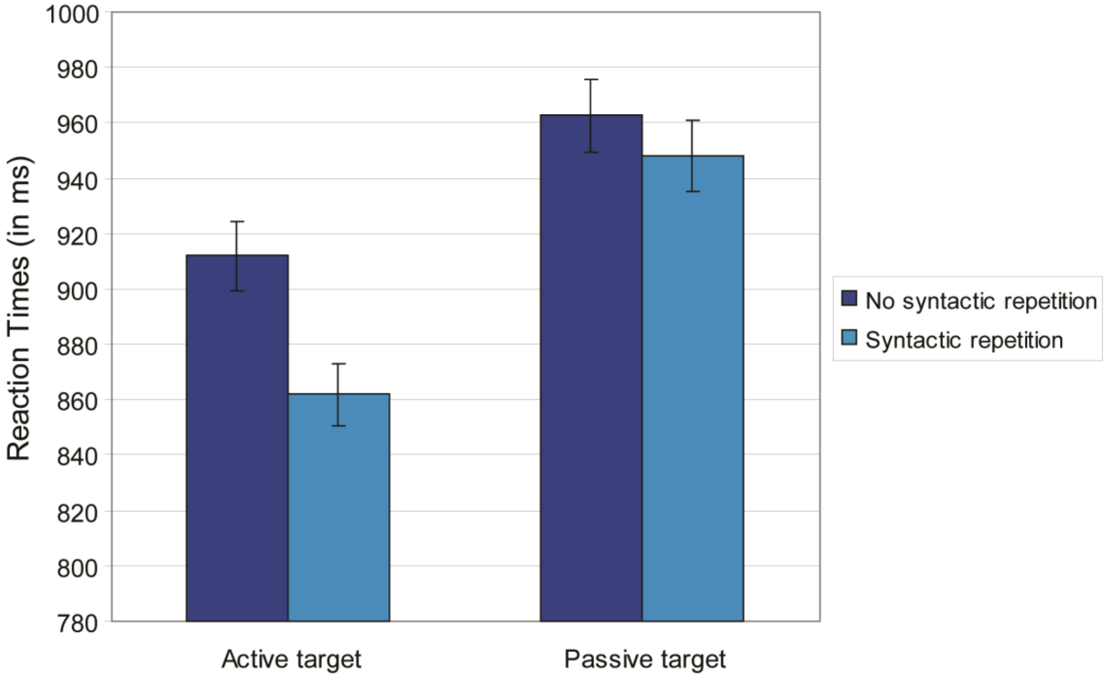

Figure 3. The mean response latencies (with the standard error of the mean) in the conditions with no syntactic repetition and syntactic repetition between prime and target, separately for active and passive target sentences.

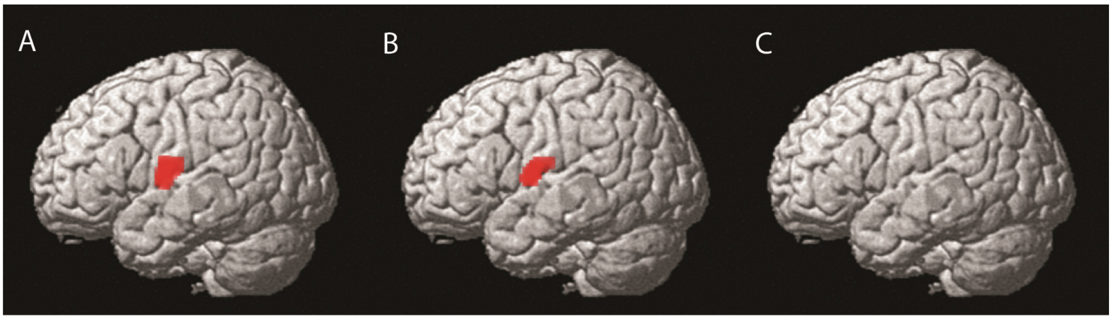

Figure 4. (A) Main effect of syntax repetition. The left insula showed more activation for repeated compared to novel syntactic structures (i.e. repetition enhancement); (B) Effect of syntactic repetition for active sentences. For active transitive sentences the left insula showed more activation for repeated compared to novel syntactic structures (i.e. repetition enhancement); (C) Effect of syntactic repetition for passive transitive sentences. For passive transitive sentences there were no repetition effects in the brain for repeated compared to novel syntactic structures.

fMRI results

Whole-Brain Analysis. For the whole brain comparisons, we used a cluster-level threshold corrected for multiple comparisons of $P < .05$ and an uncorrected voxel-wise threshold of $P < .001$.

As displayed in Table 1 and illustrated in Figure 4A, there were no repetition suppression effects for sentences with a repeated syntax. There was *more* activation for sentences with a repeated syntax than for sentences with a novel syntax (i.e. repetition enhancement) in the left insula (BA 48). The repetition effect for syntactic structures did not interact with verb repetition, the number of intervening trials, or a combination of these factors. Also, there was no interaction between syntax repetition and the target structure. Since we predicted that the syntactic repetition effect would depend on the target structure, we looked at the syntactic repetition effect for actives and passives separately (Table 1 and Figure 4B and C). These planned comparisons revealed that for actives there were no repetition suppression effects but there was a repetition enhancement effect in the left insula (bordering left Rolandic operculum, BA48) and for passives there were no repetition effects.

As displayed in Table 2 and Figure 5A, there was *less* activation for sentences with repeated verbs than for sentences with novel verbs (i.e. repetition suppression) in the left middle and inferior temporal gyrus (BA 21/37), in the left inferior frontal gyrus (BA 45/47) and in the left precentral gyrus (BA 6). There was also suppression for repeated verbs in bilateral anterior and middle cingulum (BA 23/24/25) and in the right supplementary motor area (BA 32). Repetition effects in the opposite direction were found in a number of other regions. There was *more* activation for sentences with repeated verbs than for sentences with novel verbs (i.e. repetition enhancement) in the right precuneus (BA 23), bilateral inferior and superior parietal regions and angular gyrus (BA 39/40), in the right middle and inferior frontal gyrus (BA 9/10/45) and the left middle and superior frontal gyrus (BA 10/11) (Figure 5B).

For transitive sentences following two intervening trials there was more activation than for sentences following no intervening trials in a network of bilateral regions: middle and anterior cingulum and precuneus (BA 24/29), middle and superior frontal gryus (BA 9/46), precentral gyrus (BA 6/4) and superior temporal gyrus (BA 22/42/48) (Table 3 and Figure 6A). For passive transitive sentences more than for active transitives there was activation in a network of regions bilaterally extending over the postcentral and middle/superior temporal region and the insula (BA 3/22/48), in the bilateral middle cingulum and left supplementary motor area (BA 32/6) and in the left thalamus (Table 4 and Figure 6B).

ROI Analysis. An ROI analysis in the left inferior frontal gyrus did not reveal any significant main effects or interaction effects. An ROI analysis in the left middle temporal gyrus only revealed the following effect: a main effect of verb repetition ($F_{1,23} = 38.37$, $P < .001$) showing that there is repetition suppression in this region for repeated verbs.

Table 1

Anatomical label	BA	global and local maxima			cluster-level		voxel-level
		x	y	z	K	P(corr)	Z
Main effect syntax repetition (repetition suppression: no syntactic repetition > syntactic repetition)							
no significant clusters							
Main effect syntax repetition (repetition enhancement: no syntactic repetition > syntactic repetition)							
					280	.003	
L insula	48	-40	-4	8			4.39
L insula	48	-30	-6	16			4.37
L insula	48	-36	-14	14			3.86
Interaction syntax repetition by verb repetition							
no significant clusters							
Interaction syntax repetition by intervening trials							
no significant clusters							
Interaction syntax repetition by verb x intervening trials							
no significant clusters							
Interaction syntax repetition by target structure							
no significant clusters							
Effect of syntax repetition for actives (repetition suppression: no syntactic repetition > syntactic repetition							
no significant clusters							
Effect of syntax repetition for passives (repetition suppression: no syntactic repetition > syntactic repetition							
no significant clusters							
Effect syntax repetition for actives (repetition enhancement: no syntactic repetition > syntactic repetition							
					226	.009	
L Rolandic operculum/L insula	48	-42	-4	10			4.59
L insula	48	-32	-6	16			3.76
L insula	48	-34	-12	16			3.63
Effect syntax repetition for passives (repetition enhancement: no syntactic repetition > syntactic repetition							
no significant clusters							

Note: Listed are the MNI-coordinates for three local maxima for each significant cluster in the relevant comparisons (*P*<.05 corrected cluster-level, threshold *P*<.001 uncorrected voxel-wise). Anatomical labels are derived from the Automated Anatomical Labeling map (Tzourio-Mazoyer et al., 2002) and from Brodmann's atlas.

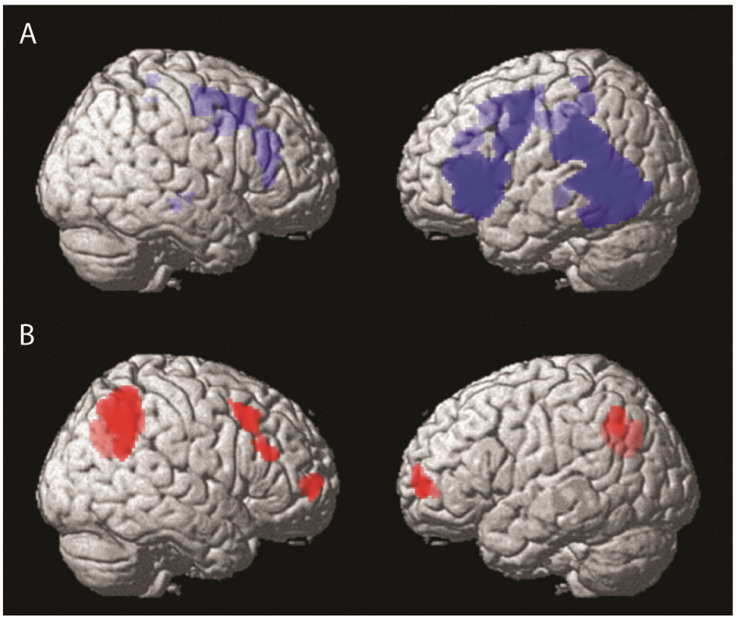

Figure 5. (A) Main effect of verb repetition (repetition suppression). Regions showing less activation for sentences with repeated compared to novel verbs; (B) Main effect of verb repetition (repetition enhancement). Regions showing more activation for sentences with repeated compared to novel verbs.

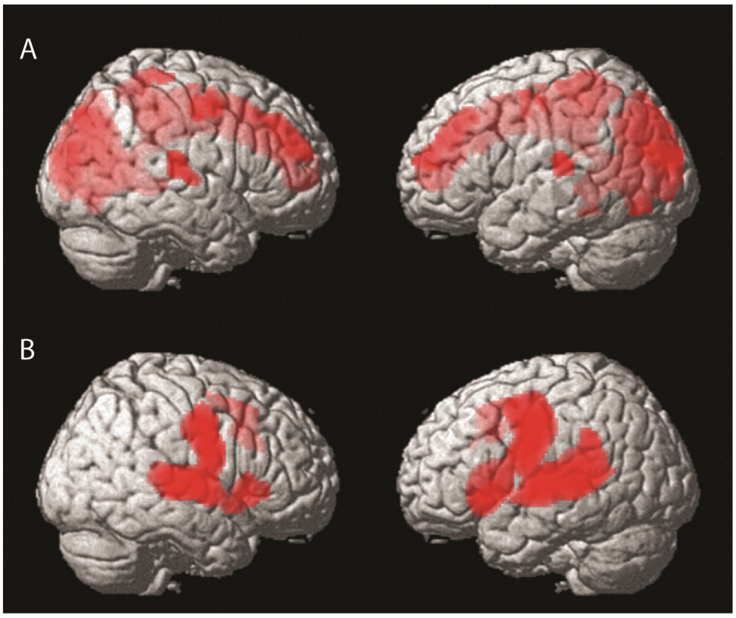

Figure 6. (A) Main effect of the number of intervening trials. A bilateral network of regions shows more activation for transitive sentences following two intervening trials (intransitive and locative sentences) than for transitive sentences following no intervening trials; (B) Main effect of target structure. A bilateral network of regions shows more activation for passive transitive sentences than for active transitive sentences.

Table 2

Anatomical label	BA	global and local maxima			cluster-level		voxel-level
		x	y	z	K	P(corr)	Z
Main effect verb repetition (repetition suppression: no verb repetition > verb repetition)							
					3739	.000	
L mid temp	21	-56	-44	2			7.80
L inf temp	37	-58	-54	-4			7.00
L mid temp	21	-52	-46	16			4.66
					2088	.000	
L inf front (pars orbitalis)	47	-46	22	-8			6.37
L inf front (pars triangularis)	47	-36	26	-2			6.37
L inf front (pars triangularis)	45	-46	28	8			5.59
					673	.000	
R supp motor area	32	2	10	54			5.71
L mid cingulum	24	-4	8	34			3.91
R mid cingulum	32	10	12	38			3.53
					622	.000	
L precentral	6	-46	-2	44			4.92
L precentral	6	-36	-2	44			4.47
L precentral	6	-44	-4	56			4.44
					362	.001	
R ant cingulum	24	8	30	16			4.39
L ant cingulum	24	-2	30	28			4.35
R ant cingulum	25	6	30	4			3.90
					194	.019	
n/a	n/a	-4	-28	-2			4.23
n/a	n/a	14	-22	-12			3.37
n/a	n/a	8	-24	-6			3.34
					179	.026	
L mid cingulum	23	-10	-26	40			4.14
L mid cingulum	23	-6	-16	40			3.99
Main effect verb repetition (repetition enhancement: no verb repetition > verb repetition)							
					934	.000	
R precuneus	23	4	-60	32			6.11
					1292	.000	
R angular	40	38	-56	40			5.12
R inf parietal	39	56	-56	42			4.96
R sup parietal	40	38	-58	56			4.69
					330	.001	
R mid front	9	42	18	50			4.55
R mid front	9	50	18	44			4.51
R inf front (pars triangularis)	45	48	32	22			3.97
					205	.015	
L mid frontal	10	-38	60	4			4.55
L sup frontal	10/11	-24	54	4			3.79

L mid front	10	-34	60	14			3.25
					186	.022	
R mid frontal	10	32	60	4			4.31
R mid frontal	10	30	56	6			4.31
R mid frontal	10	36	60	2			4.28
					156	.044	
L angular	40	-38	-56	40			3.96
L angular	39	-44	-60	48			3.33
L angular	39	-48	-62	48			3.26

Note: Listed are the MNI-coordinates for three local maxima for each significant cluster in the relevant comparisons (P<.05 corrected cluster-level, threshold P<.001 uncorrected voxel-wise). Anatomical labels are derived from the Automated Anatomical Labeling map (Tzourio-Mazoyer et al., 2002) and from Brodmann's atlas.

Table 3

Anatomical label	BA	global and local maxima			cluster-level		voxel-level
		x	y	z	K	P(corr)	Z
Main effect intervening trials							
					16980	.000	
L precuneus	29	-4	-48	12			5.99
Mid cingulum	24	0	8	34			5.05
R ant cingulum	24	2	36	22			4.76
					663	.000	
R sup front	46	28	46	22			4.78
R mid front	9/46	30	40	34			4.14
R mid front	9/46	34	30	40			3.75
					396	.000	
R precentral	6	38	0	46			4.68
R precentral	6	46	-8	50			4.02
R precentral	4	52	-12	44			3.49
					748	.000	
L mid front	46	-28	52	16			4.61
L mid front	9	-26	34	40			4.56
L mid front	46	-26	42	28			4.43
					260	.005	
R sup temp	42	60	-24	14			4.03
R sup temp	22	56	-24	10			4.02
R sup temp	22	60	-16	6			3.66
					234	.008	
L sup temp	48	-52	-24	12			3.96
L sup temp	42	-58	-24	16			3.95
L sup temp	48	-50	-28	12			3.92
					169	.033	
L precentral	6	-36	-4	-44			3.70

L sup front	6	-24	-4	48			3.65
L precentral	6	-34	-4	56			3.46
Main effect target structure (passives > actives)							
					7319	.000	
L postcentral	3	-44	-14	38			Inf
L mid temp	22	-54	-36	8			Inf
L insula	48	-32	18	8			5.44
					3705	.000	
R postcentral	3	44	-12	36			Inf
R sup temp	22	68	-20	2			6.70
R insula	48	44	14	0			4.58
					940	.000	
L supp motor area	6	-2	2	56			6.19
R mid cingulum	32	12	14	36			4.83
L mid cingulum	32	-10	14	34			4.39
					219	.011	
L thalamus	n/a	-14	-14	10			5.12

Note: Listed are the MNI-coordinates for three local maxima for each significant cluster in the relevant comparisons ($P<.05$ corrected cluster-level, threshold $P<.001$ uncorrected voxel-wise). Anatomical labels are derived from the Automated Anatomical Labeling map (Tzourio-Mazoyer et al., 2002) and from Brodmann's atlas.

Discussion

In this study we investigated the behavioural and neuronal reflections of syntactic priming of transitive sentences. We did this by investigating response latency effects and fMRI adaptation effects for the repetition of syntactic structures, and the influence on these of verb repetition and the number of intervening trials. Behaviourally, we found faster response latencies for sentences with repeated syntactic structures than for sentences with novel syntactic structures. Planned comparisons of the simple effects revealed that only for active transitives but not for passive transitives the effect was significant. These behavioural effects did not depend on whether the verb between prime and target was repeated, or whether there were intervening trials. At the neuronal level, there were no effects of repeated syntactic structures in the left IFG or left MTG. There was more activation in the left insula (BA 48) for sentences with repeated syntactic structures than for sentences with novel syntactic structures. Moreover, this repetition enhancement effect was stronger for actives than for passives. These results are puzzling and do not support any definite conclusions about the mechanisms driving syntactic priming.

Behavioural effects

In the present study we did not allow our participants to choose the syntactic structure they produced, so the behavioural syntactic priming effects could only be reflected in response latencies. In line with previous research, we found faster response latencies for syntactically primed actives but not for passives (see Chapter 2: Segaert et al., 2011). We did not find evidence for a lexical boost of the syntactic priming effects in response latencies and we did find evidence that the effects were long lasting (i.e. lasting over two intervening trials).

Evidence for the absence of a lexical boost of syntactic priming effects in response latencies corroborates the findings of the experiments reported in Chapter 2. In these earlier experiments, we found that there is a lexical boost of syntactic priming effects in response tendencies but no lexical boost of effects in response latencies. This is the first study to investigate the longevity of syntactic priming effects in response latencies. Evidence that not just syntactic priming effects in response tendencies but also effects in response latencies can be long-lived, is important to account for by theories of syntactic priming.

The absence of neuronal syntactic repetition effects in left IFG and left MTG

We did not find any repetition suppression effects for repeated syntactic structures in left IFG or left MTG - not in the whole brain analysis and also not in the ROI analysis. This is surprising because effects in the left IFG and left MTG are commonly found in studies investigating syntactic processing. In each of the four fMRI studies we previously performed, we found syntactic repetition suppression effects in these two regions (Menenti et al., 2011; Menenti et al., submitted; Segaert et al., submitted; Segaert et al., 2011). We are therefore puzzled to not find repetition effects in these two regions in the present study.

In terms of methods and materials, the present study is very similar to our four previous neuroimaging studies containing a syntactic priming manipulation (Menenti et al., 2011; Menenti et al., submitted; Segaert et al., submitted; Segaert et al., 2011): the number of subjects, the stimuli and the stop-light task are identical. There is one difference however between the present study and our previous studies. In our previous studies, blocks of transitive sentences were presented alternately with blocks of filler sentences (i.e. intransitive and locative sentences). In the present study, the ratio of transitive versus filler sentences was similar but they were mixed instead of presented in blocks.

All syntactic priming studies typically have blocks of filler trials in between blocks with syntactic priming trials, and these blocks of filler trials consist of more than just two fillers (Bernolet, Hartsuiker, & Pickering, 2009; Bock, 1986; Bock et al., 2007; Bock & Griffin, 2000; Bock & Loebell, 1990; Bock, Loebell, & Morey, 1992; J. Boyland & J. Anderson, 1998; Hartsuiker & Kolk, 1998; Menenti et al., 2011; Menenti et al., submitted; Segaert et al., submitted; Segaert et al., 2011; Segaert et al., 2011; Segaert, Weber, Cladder-Micus, & Hagoort, submitted). Larger blocks of fillers sentences may be necessary to bring about observable syntactic priming effects. They may serve as a means to wash out the syntactic priming manipulation of the preceding block of target sentences. Maybe only then it is possible to observe the added effect of a syntactic priming manipulation over several blocks target sentences. The absence of blocks of filler sentences may thus have been the reason that we do not observe syntactic repetition effects in left IFG and left MTG in the present study. This suggestion would have to be tested in future research.

We found a repetition enhancement effect for syntactic repetition in the left insula, which was stronger for active sentences than for passive sentences. A repetition enhancement effect in the left insula is surprising both in terms of location and direction. It is so far unclear how the left insula contributes to syntactic processing. Iijima, Fukui and Sakai (2009) and Moro et al. (2001) found involvement of the left inferior frontal gyrus extending into the left insula and other regions during syntactic computations in comprehension. During syntactic encoding in production, Haller at al. (2005) found involvement of Brodmann's areas (BA) 44/45 of the left inferior frontal gyrus, as well as left BA 6, BA 7 and right insula (BA 13). Right inferior frontal areas including the right insula have also been associated with processing syntactic relations in music (Tillmann et al., 2006). No study has previously found the left insula associated with syntactic processing while the left IFG was not involved.

We can only speculate on why the repetition of syntactic structures led to an enhancement instead of a suppression effect in the left insula. In Segaert, et al. (submitted) we reviewed the variables that determine the direction of repetition effects. We believe that the variable of attention might have played a role in our study. In the present study, the transitive sentences were mixed with filler sentences and therefore the picture description task may have been more difficult (compared to previous studies, where we found repetition suppression effects). Active transitives may have drawn attention as they stood out as friends in the mist of the foes. Actives are used more frequently than passives and can therefore be considered to be the more easy syntactic alternative (Cornelis, 1996). In two previous studies, repetition enhancement instead of suppression was observed under conditions possibly involving different attentional task demands (Kouider, Dehaene, Jobert, & Le Bihan, 2007; Nakamura, Dehaene, Jobert, Le Bihan, & Kouider, 2007). For phonological priming, Kouider et al. (2007) found repetition enhancement in the left inferior frontal gyrus and anterior insula. Also in their study the condition under which enhancement was observed was standing out from the others, leading the authors to suggest that attention might have played a role. For masked word priming using the exact same stimuli and masking conditions, Nakamura et al. (2007) found repetition suppression in the parietotemporal cortex for a semantic categorization task and repetition enhancement for a reading aloud task. Nakamura et al. (2007) suggest that additional cognitive processes like self-monitoring during reading aloud may be responsible for the enhancement effect, or alternatively, the attentional task demands of reading aloud may be higher than of semantic categorization.

Neuronal effects of verb repetition, intervening trials and target structure

We did not find any regions showing an interaction between the effect of syntactic repetition and verb repetition, or between the effect of syntactic repetition and intervening trials, or between the effect of syntactic repetition and target structure. However, there were regions showing a main effect of verb repetition, intervening trials or target structure.

Verb repetition was associated with repetition suppression in the left middle and inferior temporal gyrus (BA 21/37), in the left inferior frontal gyrus (BA 45/47) and in the left precentral gyrus (BA 6), all replicating previous results (Menenti et al., submitted). There was also suppression for repeated verbs in the bilateral anterior and middle cingulum (BA 23/24/25) and in the right supplementary motor area (BA 32). In addition to these repetition suppression effects, there were also enhancement effects in the right precuneus and bilateral parietal and frontal regions when the verb was repeated. These enhancement effects very likely reflect the contribution of explicit memory (Segaert, Weber, de Lange, et al., submitted).

A bilateral network of regions including the cingulate cortex and dorsolateral prefrontal cortex showed greater activation during transitive sentences following two intervening trials than during transitive sentences following another transitive sentence. We conjecture that this increased activation is likely associated with exerting control over task-switching. During the majority of intervening trials, intransitive sentences were produced. Unlike transitive sentences, intransitive sentences contain only one actor and consequently participants do not have to perform the stop-light naming task. Studies on verbal control in the context of the Stroop task have reported activation in a network of regions, commonly involving the cingulate cortex and dorsolateral prefrontal cortex (BA 9/46) (Botvinick, Cohen, & Carter, 2004; MacLeod & MacDonald, 2000). These regions operate during tasks involving higher levels of mental effort and detect events for which a shift of attention focus and strengthened top-down control is needed.

Bilateral postcentral and temporal regions, insula and middle cingulum were more activated for passive than active transitives. The same holds for the left SMA and thalamus. This increased activation probably reflects that passive transitives are the more difficult syntactic alternative because they are less frequently processed (Segaert et al., 2011) and/or that passives sentences contain more words/syllables than actives (Menenti et al., 2011).

Implications for our ideas on the mechanism driving syntactic priming

Whether the principal mechanism behind syntactic priming is implicit learning or residual activation has been a matter of debate in the literature. A neuroimaging study could have been an ideal method to find possible evidence for a multifactorial account of syntactic priming: different syntactic priming mechanisms could be reflected in the neuronal activity of different regions in the brain and/or with different time courses. More specifically, we investigated whether there were brain regions showing an interaction between the effect of syntactic repetition and the effect of verb repetition. Evidence for a lexical boost of syntactic repetition effects at the neuronal level would have provided support for the residual activation account. We also investigated whether there were brain regions showing an interaction between the effect of syntactic repetition and the longevity of priming. Evidence for the existence of long-lived effects would have provided support for the implicit learning account. The absence of any effects of syntactic repetition in the left IFG and left MTG, regions commonly associated with syntactic processing, rendered the results of this study somewhat uninterpretable. A possible reason for this may have been a specific aspect of our study design, namely the absence of filler blocks. We therefore are not able to draw any conclusions with regards to the mechanisms driving syntactic priming. From the results of this study, we are furthermore unable to interpret the relationship between syntactic priming effects at the behavioural level and the effects at the neuronal level.

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Chapter 7
Summary and discussion

In this dissertation I investigated behavioural and neuronal reflections of syntactic processing during language production as well as comprehension. I investigated the workings of syntactic priming and furthermore used syntactic priming as a tool to answer questions about syntactic processing. The results of the studies reported in Chapter 2 through 6 present a number of constraints for neurocognitive theories of syntactic processing.

The implications for neurocognitive theories of syntactic processing

A competition model of syntactic priming

Syntactic priming effects provide us with a window onto the representations and workings of syntactic processing. The most important syntactic processing theories which explicitly specify the mechanism underlying syntactic priming are the implicit learning theory (Chang, Dell, & Bock, 2006; Chang, Dell, Bock, & Griffin, 2000) and the residual activati on theory (Pickering & Branigan, 1998). Crucially, these theories are based almost exclusively on reports of behavioural syntactic priming effects on response tendencies. In the literature, reports of syntactic priming effects on response latencies are scarce (Corley & Scheepers, 2002; Smith & Wheeldon, 2001; Wheeldon & Smith, 2003).

In Chapter 2 and 3, I reported three behavioural experiments using a novel approach to syntactic priming, simultaneously measuring response tendencies and response latencies on the same trials. The results of these three experiments provide converging evidence for a striking dissociation between the two measures. A critical determiner of the relationship between the two measures is the frequency of a syntactic structure, or put forth another way, the preference for this syntactic structure. In the first two experiments (Chapter 2), I investigated syntactic priming effects of transitive sentences in Dutch. Active sentences are used much more frequently and thus preferred over passive sentences. The first experiment revealed that there were priming effects in response tendencies for passives and in response latencies for actives. The second experiment demonstrated that this discrepancy in results had to do with the different frequency of actives versus passives per se, not with another difference between these two alternative structures (e.g. passives are stylistically marked). In the second experiment, participants gained additional experience with passives during a training session. This manipulation made passives more frequent. Syntactic priming then occurred for both actives and passives in response tendencies as well as in response latencies. In the third experiment (Chapter 3), I investigated ditransitive instead of transitive sentences and demonstrated that the frequency of a structure does not necessarily have an ‘all or none’ influence on syntactic priming effects. For some ditransitive verbs in German the double object dative construction is preferred, while for others the prepositional object dative construction is preferred. In the response tendencies there was an inverse (negative) effect of preference: there were stronger syntactic priming effects for primes in the less preferred structure, given the syntactic preference of the prime verb. In the response latencies there was a positive effect of preference: there were stronger syntactic priming effects for primes in the more preferred structure, given the syntactic preference of the prime verb. Chapter 3 also touches upon the relationship between lexical and syntactic processing, since the findings demonstrate that syntactic preference plays a role even when it is specific for a particular verb. We will revisit the implications of this in a following section.

The findings of the three experiments reported in Chapter 2 and 3 inform us about the functions of syntactic priming. The benefit of experience with a less frequent structure lies in an increased ability for a speaker to select this structure for production. Speakers gain experience with the infrequent structure and learn it. With this, syntactic processing implements a type of 'affirmative action' (Ferreira, unpublished). This way, less frequent syntactic structures (the minority group) keep being used. The benefit of experience with a more frequent structure on the other hand, lies in the ability to produce this structure faster. In other words, the benefit for frequent structures lies in production fluency (Levelt & Kelter, 1982).

Neither of the traditional theories (implicit learning theory: Chang et al., 2006; residual activation theory: Pickering & Branigan, 1998) can adequately explain the results of Chapter 2 and 3. I proposed a new competition-based model of syntactic processing that is able to account for all these syntactic priming findings. This model proceeds from rather standard assumptions regarding the make-up and functioning of the units in computational neural network models (Anderson, 1996; McClelland & Rumelhart, 1981). A first central tenet of the model is that there is competition between syntactic alternatives, or put differently, that syntactic alternatives inhibit each other. A second tenet of the model is that grammatical encoding proceeds in two sequential stages: (1) a selection stage, during which one of the alternative syntactic constructions is selected, and (2) a planning stage, during which production of the selected construction is prepared. This implies that the choice of a syntactic structure is determined exclusively during the selection stage. The response latency, on the other hand, depends on the course of events in both the selection stage and the planning stage: the durations of these stages contribute to the response latency as additive effects. These two central tenets make it possible to find different outcomes of syntactic priming in response tendencies versus latencies.

A shared neurobiological infrastructure for syntactic processing in speaking and listening

Syntactic processing has traditionally been investigated separately in language comprehension and production, often with the underlying theoretical assumption that these are two separate systems. But contrary to this widespread belief, the findings of Chapter 4 convincingly demonstrate that syntactic processing in speaking and listening relies on the same neurobiological system, which involves the left inferior frontal gyrus and left middle temporal gyrus. Processing syntax in one modality leads to adaptation effects in the other modality. This was demonstrated by showing the absence of an interaction between syntactic repetition effects and modality change in Chapter 4, a finding which was replicated again in Chapter 5.

Interesting in this respect is a recent study by Kempen, Olsthoorn and Sprenger (in press) demonstrating that the mechanism that constructs (in production) or deconstructs (in comprehension) syntactic structures and the short-term storage of the result of this computation is shared between the modalities. This indicates that there is a common grammatical workspace for speaking and listening.

The results reported in Chapter 4 and the findings of Kempen et al. (in press) taken together strongly support the notion of a shared neurobiological substrate and shared cognitive mechanisms for syntactic processing in speaking and listening. These findings have widespread consequences for all cognitive theories on syntactic processing in speaking as well as listening. They provide support for theoretical arguments that there is a shared cognitive system with shared representations (interactive alignment model of dialogue, Pickering & Garrod, 2004) and/or processes manipulating these representations (Kempen, 2000). Unmistakably, it is now time to revise theories that presuppose separate mechanisms for syntactic processing aspects of language production and comprehension.

These findings might raise one question, though. In daily life, we produce and comprehend language, seemingly at the same point in time. For instance, we sometimes reply to a conversation partner before she finishes speaking. A phenomenon like this leaves us with the intuition that we are in fact capable of simultaneously comprehending and producing language. This intuition is at first sight hard to reconcile with the idea that we only have one syntactic processor for speaking and listening. Simultaneity may only be there on the surface however, while in fact our processor is switching between two tasks. Speaking and listening can time-share the workspace for syntactic processing (Kempen et al., in press).

The lexicalist nature of syntactic processing

In Chapter 3 as well as Chapter 5, I investigated the relationship between lexical and syntactic processing. The results of Chapter 3 demonstrate that the syntactic preference which is tied to specific verbs determines syntactic priming effects. This provides an argument for so-called lexicalist grammar frameworks. Lexicalist grammar formalisms have found increasing support in recent years (Jackendoff, 2002). In these frameworks, the distinction between traditional grammar rules and lexical items is blurred or has disappeared completely. Lexicalist grammars propose that syntactic information is retrieved from the mental lexicon, the repository of information associated with individual lexical items, including their syntactic information. The competition-model I proposed to explain behavioural syntactic priming effects in response tendencies and latencies (see Chapter 2), is lexicalist in nature and can thus also explain the influences of verb-specific syntactic preferences.

In Chapter 5 I also investigated the relationship between lexical and syntactic processing, more specifically, the presence of the lexical boost. During sentence production as well as comprehension, I measured the extent of fMRI adaptation to repetition of verb-headed syntactic constructions with vs. without repetition of the verb. Unaffected by the processing modality, results in left inferior frontal and left middle temporal gyrus showed that neuronal syntactic repetition effects for active sentences were boosted by verb repetition, but passive sentences were not boosted by verb repetition. I must note that these findings may be tainted by a confound in the materials. We measured syntactic repetition effects for active and passives sentences in Dutch. In Dutch, the main verb is mentioned in between the two protagonists in an active sentence (*e.g. De jongen kust het meisje*) but after the two protagonists in a passive sentence (e.g. *Het meisje wordt door de jongen gewurgd*). (It is possible to mention the verb in between the two protagonists in a passive sentence in Dutch, e.g. *Het meisje wordt gewurgd door de jongen*, but this construction occurs infrequently.) Thus, for passive sentences, the participants could have postponed planning the main verb until after having processed the descriptions of the protagonists. It is well-known that sentence processing is incremental (Kempen & Hoenkamp, 1987; Levelt, 1989). By postponing the description of the action for passives, the participants could, in effect, spread out processing load over a longer time interval, as compared to actives, where the main verb often must have been planned early in the sentence. This may have contributed to the absence of a lexical boost for passive sentences.

A new study is necessary to test whether this confound in the materials indeed contributed to the outcome of the study. In Dutch, for active as well as passives sentences in the past tense, the verb is placed after the protagonists of the transitive event (active sentence: *e.g. De jongen heeft het meisje gewurgd*; passive sentence: *Het meisje werd door de jongen gewurgd*). Another test bed could be to use English materials instead. In English, both for active and passive sentences the main verb is mentioned in between the two protagonists. A study using materials in which there is no linear order confound between syntactic alternatives will be necessary to gain more insight into the influence of verb repetition on neuronal syntactic repetition effects.

Small changes in design have large consequences for results

In Chapter 6, I reported an fMRI study investigating theories on the mechanism behind syntactic priming. Different mechanisms have been proposed to drive syntactic priming: implicit learning of mapping abstract syntactic frames to a message, on the one hand (Chang et al., 2006; Chang et al., 2000), and residual activation of syntactic information represented in the mental lexicon, on the other (Pickering & Branigan, 1998). In an fMRI study on language production, I investigated the possibility of a multifactorial account of syntactic priming. I investigated whether there were brain regions showing an interaction between the effect of syntactic repetition and the effect of verb repetition (see also previous section) – this would provide support for the residual activation account. I also investigated whether there were brain regions showing an interaction between the effect of syntactic repetition and the longevity of priming – this would provide support for the implicit learning account. Surprisingly, there were no effects of syntactic repetition in regions commonly associated with syntactic processing. A possible reason for this may have been a specific aspect of our study design, namely the absence of filler blocks (filler blocks are used in the design of other syntactic priming studies). The puzzling results of this study make it difficult to draw definite conclusions about the mechanisms driving syntactic priming, but demonstrate that small changes in a study design can have large consequences.

Outlook on the future

There are several questions left outstanding in this dissertation. One important question left to address in future research is the relationship between behavioural and neuronal measures of syntactic processing. Based on the studies reported in this dissertation, some groundwork has already been laid to elucidate the relationship between behavioural and neuronal measures. However, the results suggest that there is a lot more work to be done.

Behavioral production experiments demonstrate that for passive sentences there are syntactic priming effects in response tendencies, while for actives sentences there are syntactic priming effects in response latencies (Chapter 2 and Chapter 6). This distinction is not reflected in the syntactic repetition effects in the brain from which both behavioral outcomes seem to originate: on the neuronal level there are effects for active as well as passive sentences. This highlights the need to focus on both behavioural outcomes in future studies instead of on one of them.

The relationship between the influence of the lexical boost on behavioural syntactic priming effects and the influence of the lexical boost on neuronal effects is still unclear. The studies reported in Chapter 5 and 6 could have been informative in this respect, but the findings of the studies resulted in a complicated picture without a clear-cut conclusion. In Chapter 5, I investigated the presence of the lexical boost on syntactic repetition effects in the brain during production as well as comprehension. In the behavioural literature, findings of syntactic priming in comprehension seem to be almost completely lexically dependent (e.g. Arai, van Gompel, & Scheepers, 2007), while syntactic priming in production is also observed in the absence of lexical repetition (e.g. Branigan, Pickering, & Cleland, 2000). While it is difficult to find a comparable behavioral measure of production and comprehension, a measure of neuronal activity allows for a direct comparison between the two processing modalities. The magnitude of the lexical boost effect at the neuronal level was the same during listening and speaking.

Also in the fMRI study reported in Chapter 6, I aimed to investigate the lexical boost, in addition to the longevity of syntactic priming. The results of Chapter 6 were somewhat disappointing: there was no indication of any syntactic effects in regions commonly associated with syntactic processing. Therefore, this study also did not provide any further insights in the relationship between behavioural and neuronal effects.

Future studies will be needed to investigate the relationship between behavioural and neuronal effects more closely. A step forward could be made by doing neuroimaging studies using ditransitive instead of transitive sentences as stimulus materials. In a neuroimaging study, a lot of trials are needed per condition. In the neuroimaging studies reported in this dissertation (Chapters 4 through 6), a forced production paradigm was used for the transitive sentences, because 'free' production of passive sentences does not often occur. For ditransitives sentences in German, like the ones used as stimulus materials in Chapter 3, both alternative structures occur relatively frequently. These sentence materials could thus be used in a neuroimaging study in which participants produce syntactic structures freely. In this way, one could simultaneously measure behavioural effects in response tendencies, behavioural effects in response latencies and neuronal effects in the brain.

Envoi

A full account of syntactic processing cannot be developed without taking into account different behavioural and neuronal measurements of language production, and without taking into account the relationship between production and comprehension. Different measurements of language production provide us with different valuable information about the workings of syntactic processing. In the behavioural syntactic priming literature, investigations in response latencies are scarce. The experiments described in this dissertation convincingly show that it is feasible to measure response latencies in addition to response tendencies, and that information from response latencies is a necessary addition. Furthermore, neuroimaging studies investigating syntactic processing during overt language production are also a scarcity. The studies reported in my dissertation demonstrate that it is possible to correct the distortions caused by speaking out loud in an fMRI environment, and feasible to study overt sentence production in an fMRI study. Hopefully, many more studies on language production will follow.

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Chapter 8
Nederlandse samenvatting

Communiceren met gesprekspartners is iets dat we dagelijks doen. Een *spreker* start de communicatie met een bepaalde intentie of representatie van een boodschap. Deze intentie wordt over verschillende stappen omgebouwd tot een reeks van gearticuleerde klanken. Een *luisteraar* ontvangt deze stroom klanken en moet dan daaruit de betekenis en intentie van de spreker afleiden. Succesvolle communicatie steunt daarbij op meer dan het uitspreken of het begrijpen van aparte woorden. Een reeks met woorden kan op meerdere manieren gecombineerd worden tot zinnen met verschillende betekenissen. *De man wurgt de vrouw* bevat dezelfde woorden maar heeft een andere betekenis dan *De vrouw wurgt de man*. Het is dus cruciaal voor zowel de spreker als de luisteraar om niet alleen aparte woorden maar ook combinaties van woorden of zinnen te kunnen verwerken.

De informatie die we geleerd hebben over individuele woorden is opgeslagen in ons lange termijn geheugen, in ons mentale lexicon. Dat bevat informatie over hoe woorden klinken, hoe ze geschreven worden, wat hun betekenis is en ook syntactische informatie zoals de informatie dat *wurgen* een werkwoord is. Sprekers en luisteraars halen deze informatie over woorden op uit hun lange termijn geheugen. Dit ophaalproces is slechts een deel van onze taalverwerking. Het levert de bouwstenen aan voor verdere combinatieprocessen (Hagoort, 2005; Jackendoff, 2002). Deze combinatieprocessen zijn nodig om de betekenis en syntax van een zin als geheel te kunnen verwerken. In mijn proefschrift heb ik me gefocust op syntactische verwerkingsprocessen. Het bepalen van de syntactische relaties tussen woorden in de zin is een zeer belangrijk proces bij het produceren en het begrijpen van taal.

Ik heb zowel naar gedrag (hoofdstuk 2 en 3) als naar neurale processen (hoofdstuk 4, 5 en 6) tijdens syntactische verwerking gekeken. Dit zowel tijdens het produceren of construeren van syntax, als tijdens het begrijpen of ontleden van syntax. Ik heb daarbij in mijn onderzoek gebruik gemaakt van het fenomeen syntactische priming. Syntactische priming is een handige manier om syntactische verwerking te bestuderen. Syntactische priming verwijst naar de gefaciliteerde verwerking die optreedt voor zinnen met een syntactische structuur identiek aan de syntactische structuur van een voorafgaande zin (Bock, 1986). Het is gemakkelijker om een passieve zin zoals *De jongen wordt gekust door het meisje* te verwerken als de zin volgt op een andere passieve zin, dan wanneer de zin volgt op een actieve zin.

In hoofdstuk 2 en 3 heb ik in drie experimenten op gedragsniveau het fenomeen syntactische priming onderzocht. Het blijkt dat sprekers niet alleen een voorkeur vertonen voor het herhalen van een syntactische structuur in plaats van een alternatief te produceren, maar dat sprekers de herhaalde syntactische structuur ook sneller kunnen produceren. De effecten worden in sterke mate bepaald door de frequentie waarmee een bepaalde syntactische structuur normaal gezien in ons taalgebruik voorkomt.

In hoofdstuk 2 heb ik gekeken naar syntactische priming effecten van actieve *(bv. De man wurgt de vrouw)* en passieve *(bv. De vrouw wordt gewurgd door de man)* zinnen in het Nederlands. Voor alle transitieve werkwoorden die we in een actieve of passieve zin kunnen gebruiken, wordt de actieve syntactische structuur veel frequenter gebruikt. In hoofdstuk 3 heb ik syntactische priming effecten van ditransitieve zinnen in het Duits onderzocht. Het is zo dat voor sommige werkwoorden de prepositie-object datief frequenter wordt gebruikt *(bv. 'Die Frau verkauft die Blumen an den Mann'* – Nederlandse vertaling: *De vrouw verkoopt de bloemen aan de man*), terwijl voor andere werkwoorden de object-object datief frequenter wordt gebruikt *(bv. 'Der Junge liefert dem Mädchen ein Paket'* – Nederlandse vertaling: *De jongen levert het meisje een pakketje*). De frequentie van de syntactische structuren, zij het voor individuele ditransitieve werkwoorden (hoofdstuk 2) of voor de gehele categorie van transitieve werkwoorden (hoofdstuk 3), bleek een grote rol te spelen bij syntactische priming. Wanneer een spreker een niet-frequente syntactische structuur produceert, zal deze ervaring er vooral toe leiden dat de spreker deze structuur ook vaker zal verkiezen boven een alternatief en in mindere mate tot een versnelde productie. Wanneer een spreker een frequente syntactische structuur produceert, zal deze ervaring er vooral toe leiden dat de spreker deze structuur sneller zal produceren, en in mindere mate dat de spreker de structuur vaker zal verkiezen boven een alternatief.

Deze resultaten geven ons informatie over de voordelen of functies van syntactische priming voor sprekers (Ferreira & Bock, 2006). Het voordeel van ervaring met een niet-frequente syntactische structuur ligt dus vooral in een verhoogde capaciteit om deze structuur te gebruiken. Sprekers ondergaan zo impliciet een leerproces (Chang, Dell, & Bock, 2006; Chang, Dell, Bock, & Griffin, 2000). Omdat de keuze van sprekers voor structuren meer beïnvloed wordt door ervaringen met niet-frequente dan met frequente structuren, blijven de niet-frequente structuren bestaan in ons taalgebruik. Het voordeel van ervaring met frequente structuren ligt meer in een versnelling van het productieproces. Met andere woorden, het voordeel ligt in een vloeiende spraakproductie (Levelt & Kelter, 1982).

Traditionele theorieën over syntactische priming kunnen de resultaten van hoofdstuk 2 en 3 moeilijk verklaren (implicit learning theory: Chang et al., 2006; residual activation theory: Pickering & Branigan, 1998). Daarom heb ik een voorstel uitgewerkt voor een nieuw model van syntactische priming. Het eerste centrale aspect van dit model is competitie tussen alternatieve syntactische structuren die elkaar inhiberen. Het tweede centrale aspect is dat syntactische verwerking in twee sequentiële stadia verloopt: (1) een selectie stadium waarin een van de alternatieve syntactische structuren gekozen wordt, en (2) een planning stadium waarin productie van de gekozen structuur voorbereid wordt. Voor de details van dit model verwijs ik u graag naar hoofdstuk 2 en 3.

In hoofdstuk 4, 5 en 6 heb ik de neurale processen tijdens syntactische verwerking onderzocht. Daarbij heb ik gebruik gemaakt van een beeldvormingtechniek voor hersenactiviteit, genaamd functional Magnetic Resonance Imaging (fMRI). Met deze techniek kunnen we meten naar welke gebieden in het brein meer zuurstofrijk bloed gestuurd wordt terwijl het brein een taak uitvoert. Deze toevoer in zuurstofrijk bloed geeft aan dat het gebied meer actief is en dus dat het een rol speelt bij het uitvoeren van de taak.

Ik heb een bepaalde toepassing van fMRI gebruikt die fMRI adaptatie genoemd wordt. De respons van ons brein is namelijk gevoelig aan herhaling van stimuli (Grill-Spector & Malach, 2001; Henson, 2003). Wanneer een stimulus herhaald wordt aangeboden, vertoont het brein een gereduceerde respons, dit wordt *herhalingssuppressie* genoemd. Bijvoorbeeld, wanneer we twee maal naar een foto van een rode paraplu kijken, zal de respons in hersengebieden gevoelig voor de verwerking van rode paraplu's de tweede maal gereduceerd zijn. De verandering in de breinrespons wordt enkel beïnvloed door het specifieke kenmerk van de stimulus dat werkelijk herhaald wordt. Dus wanneer we eerst naar een foto van een rode paraplu kijken en dan naar een foto van een blauwe paraplu, zullen enkel hersengebieden voor de verwerking van de vorm van de paraplu, en niet de kleur, een gereduceerde respons vertonen. Op deze manier kunnen we met fMRI adaptatie zeer gespecialiseerde hersenfuncties identificeren.

Verschillende beeldvormingstudies hebben al onderzocht welke hersengebieden betrokken zijn bij syntactische verwerking (e.g. Haller, Radue, Erb, Grodd, & Kircher, 2005; Indefrey et al., 2001; Menenti, Gierhan, Segaert, & Hagoort, 2011; Noppeney & Price, 2004; Snijders et al., 2009). Deze studies hebben voornamelijk gevonden dat de left inferior frontal gyrus en left middle temporal gyrus betrokken zijn bij syntactische verwerking. In mijn dissertatie heb ik de neurobiologische basis van syntactische verwerking verder onderzocht. Met behulp van fMRI adaptatie heb ik ingezoomd op enkele specifieke karakteristieken van het proces.

In hoofdstuk 4 heb ik specifiek onderzocht of de neurobiologische basis van syntactische verwerking gedeeld wordt door taalproductie en taalbegrip. Dit heb ik getest door een vergelijking te maken van de fMRI adaptatie effecten voor herhaling van syntactische structuren binnen versus tussen verwerkingsmodaliteiten. Als spreken en luisteren inderdaad de neurale basis voor syntactische verwerking delen, dan zou verwerking van een syntactische structuur in de ene verwerkingsmodaliteit moeten leiden tot een herhalingssuppressie effect in de andere verwerkingsmodaliteit. Dit herhalingssuppressie effect zou dan even sterk moeten zijn als het herhalingssuppressie effect wanneer een syntactische structuur herhaald wordt binnen één bepaalde verwerkingsmodaliteit. En dat is ook precies wat de resultaten van hoofdstuk 4 laten zien. Dit betekent dus dat syntactische verwerking tijdens spreken en luisteren op een gedeeld neurobiologisch systeem steunen. Dit systeem omvat inderdaad de left inferior frontal gyrus en left middle temporal gyrus. Deze uitkomst heeft belangrijke implicaties voor cognitieve theorieën over syntactische verwerking. Syntactische verwerking is namelijk traditioneel apart bestudeerd voor spreken en luisteren, dikwijls vanuit een achterliggende gedachte dat dit op twee aparte systemen steunt. De resultaten van hoofdstuk 4 ondersteunen theoretische argumenten dat er een gedeeld cognitief systeem is voor syntactische verwerking tijdens spreken en luisteren, met gedeelde representaties (interactive alignment model of dialogue, Pickering & Garrod, 2004) en/of gedeelde processen die deze representaties manipuleren (Kempen, 2000).

In hoofdstuk 5 heb ik de samenwerking tussen lexicale en syntactische verwerking onderzocht. Ik heb onderzocht of de neurale activiteit in hersengebieden verantwoordelijk voor syntactische verwerking een lexicale boost laat zien van syntactische priming effecten. Syntactische priming effecten kunnen namelijk versterkt worden wanneer niet alleen de syntactische structuur van de zin, maar ook het werkwoord zelf herhaald wordt. De resultaten laten inderdaad zien dat de herhalingssuppressie effecten in de left inferior frontal gyrus en left middle temporal gyrus voor herhaalde syntactische structuren versterkt worden wanneer het werkwoord van de zin ook wordt herhaald. Echter, deze evidentie voor een samenwerking tussen lexicale en syntactische processen uitte zich voor actieve maar niet voor passieve zinnen. Een nieuwe studie zal dit verder moeten onderzoeken. Evidentie voor een samenwerking tussen lexicale en syntactische processen past binnen 'lexicalist grammar theorieën' (Jackendoff, 2002) waarin het onderscheid tussen traditionele grammaticaregels en lexicale items verdwenen is.

In hoofdstuk 6 heb ik de langdurigheid van syntactische priming effecten in het brein onderzocht. Meer specifiek: is er ook fMRI adaptatie wanneer de herhaalde syntactische structuur niet meteen volgt op de eerste verwerking van deze structuur? Dit zou ondersteuning bieden aan het idee dat het gebruik van syntactische structuren impliciet een leerproces inhoudt (Chang et al., 2006; Chang et al., 2000). De resultaten van hoofdstuk 6 waren verrassend in de zin dat er geen fMRI adaptatie effecten konden aangetoond worden voor herhaalde syntactische structuren. Een mogelijke reden kan een bepaald aspect van het studiedesign geweest zijn, meer bepaald de afwezigheid van opvulitems (die waren wel aanwezig in het design van studies die wel effecten voor syntactische priming konden aantonen). Dit suggereert dat kleine veranderingen in een studiedesign soms erg grote gevolgen kunnen hebben voor de resultaten.

De resultaten van deze dissertatie geven ons meer inzicht in hoe syntactische verwerking in zijn werk gaat. Dit helpt om de neurocognitieve theorieën over dit proces beter af te bakenen. Een theorie over syntactische verwerking kan niet volledig ontwikkeld worden zonder zowel naar gedragsmaten als naar neurale maten van taalproductie te kijken, of zonder deze in verband te brengen met taalbegrip.

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Appendix

Appendix 1: Supplementary information for Chapter 4

ROI Analysis

Methods. Menenti et al. (in press) suggests that activations related to syntactic processing in comprehension and in production are centered around MNI coordinates [-52 10 22] in LIFG and MNI coordinates [-56 -44 4] in LMTG. We used an 8-mm sphere around both MNI coordinates. Average time courses were calculated using Marsbar (http://marsbar.sourceforge.net/). For the ROI analysis at the second level we carried out a repeated measures ANOVA with the factors syntactic repetition, modality repetition, target modality and target structure on the subject contrast values using SPSS. We corrected for multiple comparisons by using a threshold for significance of $P = .05/2$.

Results. The results of the whole-brain analysis were corroborated by the results of an ROI analysis in left IFG and in left MTG with coordinates respectively [-52 10 22] and [-56 -44 4], based on Menenti et al. (in press)). Left IFG was activated less strongly for target sentences with a repeated syntax than for sentences with a novel syntax ($F_{1,23} = 11.0$, $P < .003$). There was no interaction between this effect and whether the processing modality was repeated ($F_{1,23} = .9$, $P = .35$). The ROI analysis furthermore revealed that left IFG was activated less strongly for target sentences in the comprehension modality than the production modality ($F_{1,23} = 18.8$, $P < .001$), but there was no interaction between the effect of syntactic repetition and target modality ($F_{1,23} = 1.5$, $P = .24$). Also left MTG was activated less strongly for target sentences with a repeated syntactic structure than for sentences with a novel syntactic structure ($F_{1,23} = 11.8$, $P < .002$). Again, there was no interaction between this effect and whether the processing modality was repeated ($F_{1,23} = .2$, $P = .66$). Left MTG was furthermore activated less strongly for target sentences in the comprehension modality than the production modality ($F_{1,23} = 20.2$, $P < .001$), but there was again no interaction between the effect of syntactic repetition and target modality ($F_{1,23} = 1.4$, $P = .25$). Figure 4 illustrates the ROIs and for each ROI the relative decrease in mean BOLD amplitude for repeated syntax compared to novel syntax, separately for the effect within a processing modality and the effect across processing modalities.

Discussion. The results of these ROI analyses confirm that there is a syntactic repetition suppression effect in left IFG and left MTG, within and across processing modalities to the same extent.

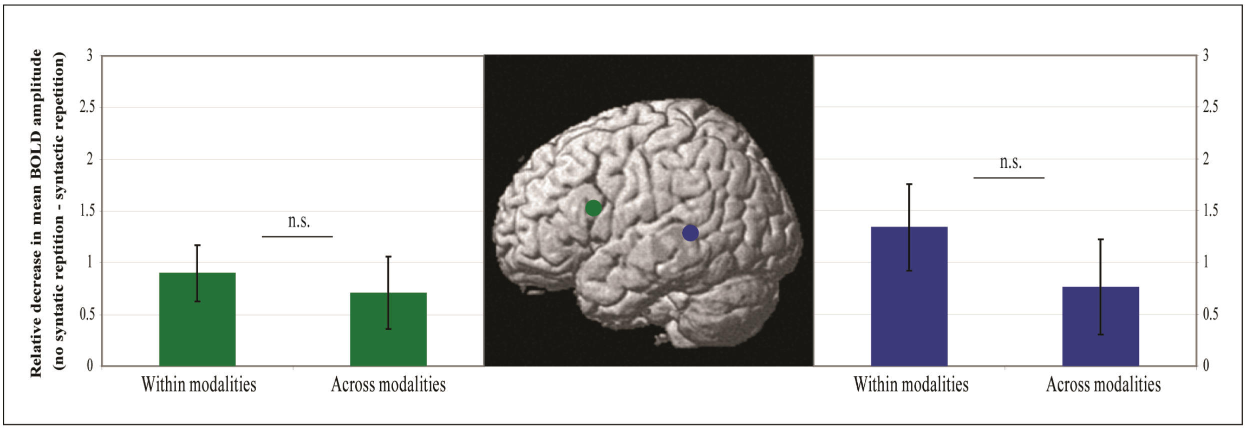

Figure 4. ROI results. ROI analysis in left IFG (colored green, MNI coordinates [-52 10 22]) and left MTG (colored blue, MNI coordinates [-56 -44 4]) revealed that there was no differential repetition suppression effect for syntactic structures within and across processing modalities (coordinates based on Menenti *et al.* in press).

Whole-Brain Analysis

Results. The following three main effects are calculated with the conditions with syntactic repetition and without syntactic repetition taken together. We found the following network of regions to be activated more during production than during comprehension: bilateral occipital regions and calcarine fissure extending into bilateral superior and middle temporal gyri, left lingual gyrus, bilateral superior parietal cortex, bilateral postcentral gyri and left supplementary motor area (Figure 5A). We found the following network of regions to be activated more during comprehension than during production: bilateral middle cingulum, precuneus, middle and superior frontal regions, postcentral gyri, angular gyri, inferior temporal gyri, caudate, insula and putamen, the left anterior cingulum and right middle temporal regions, precentral gyrus and supplementary motor area (Figure 5B). The following network of regions was activated more for sentences in a novel processing modality than sentences in a repeated processing modality and thus seems to be involved in switching between processing modalities: bilateral middle cingulum and calcarine gyri, left precuneus, insula, lingual gyrus, supramarginal gyrus, middle and superior temporal gyri (Figure 5C).

Discussion. Speaking aloud involves listening to oneself to some extent (Levelt 1989). Also, listening to sentences may involve production-based predictions (Pickering and Garrod 2007). This does not dispute the assumption of between-modality priming however, because findings demonstrate that speaking aloud cannot simply be reduced to listening and that listening cannot be reduced to speaking. The results reported in this section of the supplementary material show that a network of regions is differentially involved in speaking and listening. Moreover, Menenti et al (in press) offers a more precise comparison to illustrate this point. In this study, using the same stimuli and task, participants also produced or heard active and passive sentences. Passive sentences contain more syllables than active sentences, and therefore impose a greater load on

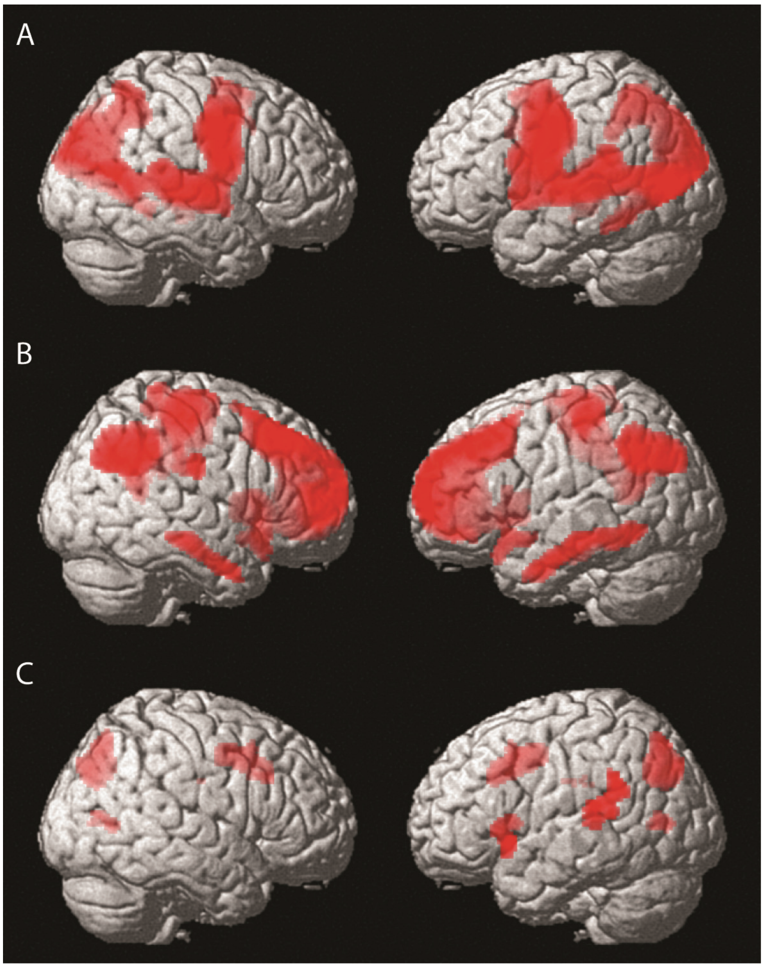

Figure 5. Whole brain results (see also Table 2). Shown are regions that show (A) more activation for production targets than comprehension targets, (B) more activation during comprehension targets than production targets, and (C) more activation for targets in a novel modality compared to targets in a repeated modality (switching between processing modalities).

speaking as well as listening. For the differential activation between passive and actives sentences, Menenti et al. (in press) found that speaking more than listening involves motor processes and listening more than speaking involves auditory sensory processes. We computed the same contrasts for the data of the present study and we replicated the results of Menenti et al. (in press). This indicates that we can speak of priming between processing modalities in our study. Self-monitoring/listening processes are not as involved during speaking as they are during listening.

Table 2

Anatomical label	BA	global and local maxima			cluster-level		voxel-level
		x	y	z	K	P(corr)	Z
Target modality (production > comprehension)							
R postcentral	4	48	-8	36	22854	.000	Inf
L postcentral	4	-48	-12	40			Inf
L mid occipital	19	-46	-78	4			Inf
L supp motor area	6	-2	0	62	572	.000	Inf
Target modality (comprehension > production)							
L ant cingulum	32	-10	44	16	14840	.000	Inf
R mid frontal	9	26	32	42			7.79
L sup frontal	9	-22	34	36			7.84
L mid cingulum	23	-2	-36	42	6445	.000	7.73
L precuneus	30	-8	-52	14			6.93
R postcentral	3	36	-30	58			5.83
R angular	39	50	-66	32	1620	.000	7.08
R angular	48	46	-48	32			5.81
L mid occipital	39	-42	-74	32	1415	.000	7.03
L angular	39	-54	-56	36			6.30
L inf temporal	37	-58	-54	-10	1043	.000	6.41
L inf temporal	20	-60	-24	-16			5.76
L inf temporal	20	-54	-12	-28			5.61
R caudate	25	10	10	6	968	.000	5.75
R insula	48	32	18	-16			4.70
R putamen	48	24	20	0			4.60
L caudate	25	-8	12	6	622	.000	5.50
L insula	48	-34	12	-12			5.13
L caudate	48	-18	16	14			3.45
L postcentral	3	-34	-32	60	661	.000	5.38
L postcentral	3	-46	-26	52			5.17
R inf temporal	20	54	-2	-32	475	.000	5.02
R mid temporal	21	62	-22	-14			4.97
R parahippocampal	20	30	-12	-24			4.05

Table 2 continued

Anatomical label	BA	global and local maxima			cluster-level		voxel-level
		x	y	z	K	P(corr)	Z
Modality switching (novel modality > repeated modality)							
L precuneus	7	-12	-68	34	745	.000	6.08
L mid cingulum	24	-6	12	38	973	.000	5.16
L mid cingulum	24	-2	0	44			4.61
R mid cingulum	24	4	22	32			3.72
n/a		-2	-28	26	177	.035	4.13
n/a		4	-16	28			3.64
L insula	48	-46	14	-6	231	.012	3.97
L insula	48	-34	20	4			3.90
L supramarginal	42	-52	-46	24	332	.002	3.77
L mid temp	22	-66	-34	8			3.63
L sup temp	22	-66	-32	16			3.56
L calcarine	17	-10	-72	8	205	.020	3.74
R calcarine	17	12	-74	10			3.50
L lingual	19	-20	-66	4			3.20

Note: Listed are the MNI-coordinates for three local maxima for each significant cluster in the relevant comparisons ($P<.05$ corrected cluster-level, threshold $P<.001$ uncorrected voxel-wise). Anatomical labels are derived from the Automated Anatomical Labeling map (Tzourio-Mazoyer N *et al.* 2002) and from Brodmann's atlas.

Appendix 2: Experimental materials

2.1. Experimental materials for Chapter 2, 4, 5, 6

List of the 36 transitive verbs depicted in the stimuli. The left column lists the verbs in the Dutch infinitive form as they were presented before the picture and the right column lists the English translations

Transitive verbs in the Dutch infinitive	English translation
aankleden	to dress
achtervolgen	to follow
afdrogen	to dry
bangmaken	to scare
bedienen	to serve
bedreigen	to threaten
betalen	to pay
begroeten	to greet
duwen	to push
fotograferen	to photograph
interviewen	to interview
helpen	to help
knuffelen	to embrace
masseren	to massage
meetrekken	to pull
meten	to measure
optillen	to lift
overeindhelpen	to help getting up
omtrekken	to pull down
natmaken	to wet
neerschieten	to shoot down
schoppen	to kick
pesten	to tease
slaan	to hit
slepen	to drag
stoppen	to stop
tekenen	to draw
naroepen	to call to
troosten	to comfort
uitzwaaien	to wave goodbye
vastbinden	to tie
verzorgen	to look after
vinden	to find
voeren	to feed
wegsturen	to send away
wurgen	to strangle

2.2. Experimental materials for Chapter 3

List of the ditransitive verbs paired with inanimate objects depicted in the stimuli. The two leftmost columns lists the verbs in the German infinitive form as they were presented before the picture and the two inanimate objects with which each verb was paired. The two rightmost columns lists their English translations.

Ditransitive verb	Object	English translations	
leihen	Fahrrad	to lend	bike
	Handy		mobile
verabreichen	Tablette	to administer	tablets
	Medizin		medication
reichen	Glühbirne	to hand	light bulb
	Pokal		trophy
liefern	Paket	to deliver	package
	Briefe		letters
zeigen	Bild	to show	painting
	Buch		book
servieren	Wein	to serve	wine
	Pizza		pizza
vorlesen	Buch	to read aloud	book
	Menü		menu
machen	Cocktail	to prepare	cocktail drink
	Pizza		pizza
suchen	Hut	to search	hat
	Schuh		shoe
verkaufen	Wein	to sell	wine
	Blumen		flowers
nähen	Socke	to sow	sock
	Kleidung		clothing
reservieren	Theaterkarten	to reserve	theater tickets
	Stuhl		chair
bauen	Bahnstrecke	to build	railway track
	Sandburg		sandcastle
schlachten	Hase	to slaughter	hare
	Schwein		pig
deuten	Formel	to interpret	formula
	Bibel		bible
bewachen	Schatzkiste	to guard	treasure chest
	Geld		money

List of publications

Segaert K., Nygard G., Wagemans, J. (2009). Identification of everyday objects on the basis of kinetic contours. *Vision Research, 49,* 417-428.

Segaert, K., Menenti, L., Weber, K., Petersson, K. M., & Hagoort, P. (2011). Shared syntax in language production and language comprehension — An fMRI study. Cerebral Cortex. Advance online publication. doi:10.1093/cercor/bhr249.

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Segaert, K., Weber, K., Cladder-Micus, M., Hagoort, P. (submitted). The influence of verb preferences on the processing of syntactic structures.

Segaert, K., Kempen, G., Petersson, K.M. & Hagoort, P. (submitted). Lexically boosted syntactic priming as measured by fMRI adaptation during language production and language comprehension.

Segaert, K.*, Weber, K.*, De Lange, F., Petersson, K.M. & Hagoort, P. (submitted). The suppression of repetition enhancement: A review of fMRI studies. **equal contribution*

Menenti, L., Segaert, K., & Hagoort, P. (submitted). The neuronal infrastructure of speaking.

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Curriculum Vitae

Katrien Segaert was born August 19th 1985 in Leuven, Belgium. After finishing high school in 2003, she studied Psychology at the University of Leuven. She completed these studies magna cum laude in 2008 with a Master's thesis on visual form and motion perception under the supervision of Prof. J. Wagemans. In October 2008, she started her PhD project in the Neurobiology of Language group at the Max Planck Institute of Psycholinguistics under the supervision of Prof. P. Hagoort. The results of her PhD research are described in this thesis. She is now a staff researcher in the same research group.

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