Syntactic priming in German–English bilinguals during sentence comprehension

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A B S T R A C T

A longstanding question in bilingualism is whether syntactic information is shared between the two language processing systems. We used an fMRI repetition suppression paradigm to investigate syntactic priming in reading comprehension in German–English late-acquisition bilinguals. In comparison to conventional subtraction analyses in bilingual experiments, repetition suppression has the advantage of being able to detect neuronal populations that are sensitive to properties that are shared by consecutive stimuli. In this study, we manipulated the syntactic structure between prime and target sentences. A sentence with a passive sentence structure in English was preceded either by a passive or by an active sentence in English or German. We looked for repetition suppression effects in left inferior frontal, left precentral and left middle temporal regions of interest. These regions were defined by a contrast of all non-target sentences in German and English versus the baseline of sentence-format consonant strings. We found decreases in activity (repetition suppression effects) in these regions of interest following the repetition of syntactic structure from the first to the second language and within the second language. Moreover, a separate behavioural experiment using a word-by-word reading paradigm similar to the fMRI experiment showed faster reading times for primed compared to unprimed English target sentences regardless of whether they were preceded by an English or a German sentence of the same structure. We conclude that there is interaction between the language processing systems and that at least some syntactic information is shared between a bilingual's languages with similar syntactic structures.

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To communicate in two languages, we have to acquire the grammar of the first language (L1) as well as the grammar of the second language (L2). It is still unclear how these two syntactic systems are organised in bilinguals. Syntactic processing in the L2 could either be largely independent of the L1 syntactic system (de Bot, 1992; Ullman, 2001), or L2 processing might involve the existing L1 grammatical processing system in the form of a co-activation or in the form of shared grammatical representations (Hartsuiker and Pickering, 2008). In the latter case the degree of recruitment of the L1 syntactic processing system might depend on the syntactic overlap between the two languages.

One way to test for co-activated or shared syntactic representations is syntactic priming. Syntactic priming is a well studied psycholinguistic paradigm in monolingual language production (Bock, 1986; Branigan et al., 1995) and comprehension (Branigan et al., 2005; Frazier et al., 1984; Luka and Barsalou, 2005). In language production, syntactic priming is found as an increased likelihood to produce a target sentence with a grammatical structure that was encountered in a preceding sentence. Priming is found even if there is no lexical or semantic overlap between the prime and the target sentence, thus giving evidence for a purely structural effect (Bock, 1986; Bock and Griffin, 2000; Pickering and Branigan, 1999). A so-called ‘lexical boost’ is found in the case of verb repetition (Hartsuiker et al., 2008; Pickering and Branigan, 1998), meaning that the priming effect is enhanced by verb repetition between prime and target, indicating some lexical influence. However, this lexical influence seems to be short-lived and an independent long-term structural priming effect seems to persist. The majority of syntactic production priming studies (Bock, 1986; Pickering and Branigan, 1998, 1999) used grammatical alternations, such as the active/passive alternation, in which the semantics of the sentences roughly stays the same, while the grammatical structure changes (e.g. The woman opened the door. The door was opened by the woman.). To date, most studies have been conducted in English or other Germanic languages, such as Dutch (Hartsuiker and Kolk, 1998) and German (Scheepers, 2003).

In comprehension, syntactic priming occurs when target sentences are preceded by sentences of the same grammatical structure in comparison to sentences of a different structure. Syntactic priming may induce faster reaction times or interpretation preferences for primed structures. Branigan et al. (2005) used a picture matching paradigm and found priming effects for relative clause-attachment ambiguities. The participants were more likely to opt for a picture of a
scene compatible with a high-attachment interpretation after a prime with a high-attachment interpretation. For example, when presented with the ambiguous phrase “The waitress prodding the clown with the umbrella”, subjects were more likely to choose the picture of the scenario where a waitress uses an umbrella to prod a clown (compared to a scene where the clown has the umbrella in his hand) after the prime “The policeman prodding the doctor with the gun” presented with a picture where a policeman has a gun and prods a doctor. These priming effects were restricted to the condition with verb repetition. Similarly, in an eye-tracking study (Arai et al., 2007), syntactic priming effects in a visual world paradigm were only found in case of verb repetition. The important role of verb repetition is supported by recent event-related potential (ERP) studies on syntactic priming in comprehension (Ledoux et al., 2007; Toole et al., 2009). Toole et al. (2009) found a syntactic priming effect in the form of a reduced P600 only in case of true verb repetition but not when the verbs in prime and target sentences were synonyms and thus closely related in meaning.

In contrast, a recent eye-movement study (Thothathiri and Snedeker, 2008) found syntactic comprehension priming effects in case of different verbs between prime and target. In this study two primes were presented before the target, suggesting that structural priming in comprehension may be a relatively weak effect that needs to be boosted by repeated presentation of a particular structure. A structural effect independent of lexical repetition was also found by Noppeney and Price (2004), in the form of faster mean reading times for primed target sentences. They used four types of structures (late and early closure clause boundary ambiguity sentences as well as simple active and reduced relative clause sentences). Like in the previous study, multiple primes were used. Priming effects were calculated over blocks of five sentences of a similar structure compared to blocks with sentences of dissimilar structures, thus potentially boosting weak effects. Thus, while the role of verb repetition has been shown to be important, the exact degree of influence on syntactic priming in comprehension remains to be addressed.

Several sentence production studies have suggested that between-language syntactic priming can reveal syntactic interaction between L1 and L2. In these studies the prime sentence was in a different language than the target sentence. Loebell and Bock (2003) showed that German–English bilinguals were more likely to produce an English double-object dative sentence (e.g. *The little boy wrote his pen pal a letter*) to describe a picture after having produced a sentence of the same structure in German (e.g. *Der reiche Bauer kaufte seinem Sohn ein Pferd*. ‘The rich farmer bought his son a horse’.) as compared to the alternate prepositional dative construction (*Der reiche Bauer kaufte ein Pferd für seinen Sohn*. ‘The rich farmer bought a horse for his son’.). Priming effects appeared in both directions from German to English and from English to German, as well as within German. In this study, priming of passive sentences failed to produce reliable effects. However, another study (Hartsuiker et al., 2004) with Spanish–English bilinguals showed a priming effect for passive sentences. The differential results of Hartsuiker et al. (2004) and Loebell and Bock (2003) might be explained by assuming that not only structural overlap between languages but also surface word-order overlap is required for priming to occur (German but not Spanish passives differ from English passives in this respect.). This possibility is supported by a recent study (Bernolet et al., 2007) on word-order effects in syntactic priming. In this study, the priming of simple relative clauses between languages was investigated. In the case of Dutch and German which have the same word order in relative clauses, priming did occur, while no priming effect was found between Dutch and English, where the word order differs. By contrast, in a study of relative clause attachments (Desmet and Declercq, 2006), priming effects despite of differences in word order were found.

A study on between-language priming of the two structures in the dative alternation in Dutch–English bilinguals (Schoonbaert et al., 2007) found equally strong syntactic priming effects within-languages (L1→L1, L2→L2) and between languages (L1→L2, L2→L1) when there was no lexical overlap, suggesting shared rather than merely co-activated syntactic representations for L1 and L2. The introduction of a verb repetition condition (within languages) or translation equivalent repetition condition (between languages) resulted in a verb boost effect of within-language priming and a slightly weaker boost from L1 to L2. From L2 to L1 the translation equivalent condition did not boost the effect.

In sum, there is considerable behavioural evidence for syntactic priming between L1 and L2 in sentence production. These data suggest at least links between the L1 and L2 syntactic representations and, in the case of equally strong between- and within-language priming effects, even shared representations. Some evidence for shared syntactic representations also comes from functional neuroimaging studies which will be discussed in the following section.

In the brain, syntactic processing in the L1 activates parts of the general language processing system that are located in the middle and superior temporal lobes as well as inferior frontal regions around Broca’s area (Friederici, 2002; Indefrey, 2004, to appear; Kaan and Swaab, 2002). Some evidence for a shared syntactic system between L1 and L2 comes from a number of hemodynamic studies comparing L1 and L2 sentence comprehension. In most studies, L2 sentence processing has been found to activate the same brain areas as L1 processing (Chee et al., 1999; Luke et al., 2002; Perani et al., 1998; Suh et al., 2007; for reviews see Abutalebi, 2008; Abutalebi et al., 2001; Indefrey, 2006). Due to the limited spatial resolution of hemodynamic methods, however, even identical L1 and L2 activation compared to a control condition cannot demonstrate that identical neuronal populations subservice L1 and L2 processing, because the smallest resolvable spatial units (voxels) still contain large numbers of neurons. It is therefore important to use new methods and paradigms to investigate whether L1 and L2 syntactic processing interact. In our experiment we used the repetition suppression paradigm to directly investigate the degree to which syntactic processes are shared between the L1 and L2.

A number of functional magnetic resonance imaging (fMRI) studies have found decreases in brain activation as a result of priming (Henson and Rugg, 2003; Schacter and Buckner, 1998), usually called repetition suppression or fMRI adaptation. In this article we will refer to the behavioural effects as syntactic priming and to the fMRI effects as repetition suppression. It is generally assumed that these neural and behavioural effects are closely related (Henson and Rugg, 2003, however see Ganel et al., 2006 for a different opinion).

Only a few studies investigated sentence or syntactic priming at the neural level and found repetition suppression effects in monolingual sentence comprehension (Dehaene-Lambertz et al., 2006; Hasson et al., 2006; Noppeney and Penny, 2006; Noppeney and Price, 2004). Repetition suppression effects for the repetition of identical sentences have been found in the superior temporal gyrus and left middle temporal gyrus (Dehaene-Lambertz et al., 2006) and a bilateral frontotemporal network including the left middle temporal gyrus (Noppeney and Penny, 2006). Hasson et al. (2006) found sentence repetition suppression effects in the left and right superior and middle temporal gyri and an additional effect in left inferior frontal regions when subjects performed a semantic judgement task. Noppeney and Price (2004) observed a genuine structural repetition suppression effect in the left temporal pole. In their study primes and targets were not identical and suppression due to repeated lexical content can thus be excluded.

While it has been shown that behavioural between-language syntactic priming effects exist in language production (Hartsuiker et al., 2004; Loebell and Bock, 2003; Schoonbaert et al., 2007), there are to date no such studies on comprehension. We investigated syntactic priming of passive sentences between L1 and L2 and within L2 in a reading time experiment as well as in an fMRI study in German–English bilinguals. In the behavioural experiment we used self-paced reading
time, a measure that has been used previously to find reliable priming effects in English for passives (Frazier et al., 1984). In the fMRI experiment we tested whether syntactically primed sentences showed a reduced blood-oxygen-level dependent (BOLD) response (repetition suppression). To maximize our chances to detect a priming effect, we investigated syntactic priming with verb repetition, as previous studies (Arai et al., 2007; Ledoux et al., 2007; Tooley et al., 2009) had demonstrated the important role of verb repetition for syntactic priming in comprehension. Moreover, because previous behavioural studies on between-language priming in production (Schoonbaert et al., 2007) had shown the strongest effect for between-language priming from L1 to L2, we chose to investigate between- and within-language priming of L2 target sentences. Furthermore, as this is the first study to look for repetition suppression effects to syntactic priming in cross-linguistic sentence comprehension, we tried to increase the possibility of finding effects by choosing two closely related and well-studied languages as well as a well-studied syntactic structure.

We predicted between-language syntactic priming effects as well as priming effects within L2, both at the behavioural and at the neural level. We expected to see repetition suppression effects in left frontal and temporal areas involved in sentence level processing.

Behavioural effects of cross-linguistic syntactic priming would give evidence for an interaction between the two syntactic processing systems. The corresponding neuroimaging effect however would lead us even one step further. The finding of repetition suppression effects for syntactic priming across languages would be a clear indication of a shared syntactic system in the sense of shared structural representations. It would mean that the very same neurons, and not only roughly similar areas, are activated for the processing of syntactic structures in both languages.

Methods

Participants behavioural experiment

In the behavioural experiment we tested 16 German–English bilinguals (10 female) of medium English proficiency. They all had a similar language background (see Table 1) and had acquired English at school as their first foreign language at on average 10.63 years (SD = 0.96) and had formal English lessons for on average 8.19 years (SD = 0.98). Thus, they were all late-acquisition bilinguals. Their proficiency was tested with the Oxford Placement test (http://www.lang.ox.ac.uk/courses/tst_english_placement.html), a multiple-choice cloze test of grammatical knowledge; mean number of mistakes = 10.64 (out of 50), SD = 4.41.

The participants received course credits or money for their participation in the experiments. All participants gave informed consent prior to participating in the study. The study was approved by the local ethics committee.

Participants fMRI experiment

In the fMRI experiment, 19 German–English bilinguals (14 female) of medium English proficiency were tested (three of these subjects were later discarded due to head movements exceeding the threshold). They all had a similar language background (see Table 2) and had acquired English at school as their first foreign language at on average 10.88 (SD = 0.96) years of age and had on average 8.3 years of formal instruction (SD = 1.01). Their proficiency was tested with the Oxford Placement test on which they made 12.5 mistakes on average (SD = 6.73). None of the participants had any known neurological impairment.

The participants received course credits or money for their participation in the experiments. All participants gave informed consent prior to participating in the study. The study was approved by the local ethics committee.

Stimuli/design

Half of the sentences were in English, the other half were their translation equivalents in German (as we had more English than German experimental sentences the ratio was reversed in the fillers to balance the number of German and English sentences overall). A trial was defined as a combination of two sentences, a prime or no-prime and a target. Target sentences always had a passive structure as this is the less preferred structure and allows for a more reliable detection of syntactic priming effects (Bock, 1986; Bock and Griffin, 2000; Chang et al., 2006). Prime sentences were passive sentences as well, while sentences from the no-prime condition had an active sentence structure (see Table 3 for stimulus examples). Passive sentences consisted of seven, active sentences of five words.

Instances of all the experimental conditions occurred equally often. The experimental design included the two factors Language combination (English–English, German–English) and Priming (active–passive, passive–passive). For the English–English condition, the verb between prime and target was the same, while between languages they were translation equivalents, while cognates were avoided. No verb was

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Gender</th>
<th>Oxford Placement Score (mistakes out of 50*)</th>
<th>Age of acquisition English</th>
<th>Years of formal English lessons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21</td>
<td>Male</td>
<td>18</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
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<td>17</td>
<td>11</td>
<td>9</td>
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<tr>
<td>3</td>
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<td>Female</td>
<td>7</td>
<td>10</td>
<td>9</td>
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<tr>
<td>4</td>
<td>20</td>
<td>Female</td>
<td>11</td>
<td>10</td>
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<td>Female</td>
<td>7</td>
<td>10</td>
<td>9</td>
</tr>
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<td>6</td>
<td>20</td>
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<td>13</td>
<td>9</td>
<td>8</td>
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<tr>
<td>7</td>
<td>21</td>
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<td>11</td>
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<td>7</td>
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<td>7</td>
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<tr>
<td>9</td>
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<td>Male</td>
<td>15</td>
<td>11</td>
<td>7</td>
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<td>Male</td>
<td>16</td>
<td>11</td>
<td>8</td>
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<td>5</td>
<td>10</td>
<td>9</td>
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<td>20</td>
<td>Female</td>
<td>6</td>
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<td>23</td>
<td>Female</td>
<td>12</td>
<td>12</td>
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<tr>
<td>14</td>
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<td>Female</td>
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<td>10</td>
<td>7</td>
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<tr>
<td>15</td>
<td>21</td>
<td>Male</td>
<td>9</td>
<td>11</td>
<td>8</td>
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<tr>
<td>16</td>
<td>20</td>
<td>Female</td>
<td>11</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>10.63</td>
<td>10.63</td>
<td>8.19</td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td></td>
<td>4.41</td>
<td>10.63</td>
<td>8.19</td>
</tr>
</tbody>
</table>

* 0–9 mistakes: advanced, 10–19 mistakes: good, 20–29 mistakes: satisfactory.
Table 3
Examples of experimental trials for the same target sentence.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Prime/no-prime</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. English–English</td>
<td>The tree was painted by the artist.</td>
<td>The moon was painted by the girls.</td>
</tr>
<tr>
<td></td>
<td>The artist painted the tree.</td>
<td></td>
</tr>
<tr>
<td>2. German–English</td>
<td>Der Baum wurde von dem Künstler gemalt.</td>
<td>The moon was painted by the girls.</td>
</tr>
<tr>
<td></td>
<td>Der Künstler malte den Baum.</td>
<td></td>
</tr>
</tbody>
</table>

repeated except in the verb repetition condition. For each subject we had 36 experimental trials per condition. Experimental trials were alternated with one to three filler sentences. The number of noun phrases in filler sentences matched the number of noun phrases in the experimental sentences; the structures of these fillers were different to those in the experimental sentences. The order of the experimental trials was randomized. As a baseline condition we inserted six to ten consonant string sentences after every 20 sentences. Eight stimulus lists were created that counterbalanced the languages and the structures that preceded a target stimulus. Moreover, each sentence content appeared in the prime as well as target position.

Behavioural experiment procedure

The experiment was run using Presentation software (Neurobehavioral Systems, www.neuro-bs.com). Participants sat in front of a personal computer. Sentences were presented word by word in a self-paced reading paradigm, in white "Arial" font of size 22 on a black background. After reading each word, subjects had to press a button, thus providing a measure of reading time. During the inter-stimulus interval a fixation cross was displayed. The length of the interval was jittered between 1.5 and 4.5 s (to mirror the fMRI experiment). Following 20% of the filler sentences, a grammaticality decision had to be made by pressing one of two buttons. Each participant saw only one of the stimulus lists.

Behavioural experiment data analysis

To test the hypothesis that reading times are faster for primed compared to unprimed sentences we conducted a reading time analysis on the reading times from the third word onwards, where the syntactic sentence structure became apparent. A 2 × 2 × 5 ANOVA with the factors Priming (primed; not primed), Language combination (English–English; German–English) and Word (word 3 to 7) was conducted on the word-by-word reading time data. Moreover, to make sure that there are no effects before the 3rd word we did a separate analysis on the first two words, with the factors Priming (primed; not primed) and Language combination (English–English; German–English). Outliers (reading times lower than: mean − 2 * SD or 90 ms; and higher than: mean + 2 * SD per word), were calculated separately for each subject and language over all experimental and filler sentences and were removed.

We conducted a separate analysis on the same data in which any effects of word length were removed by a linear regression for each subject. This was done by computing a linear regression with string length of each word as the independent variable and reading time as the dependent variable for each subject and language separately. The regression was computed over all materials (for a more detailed description of the procedure see Ferreira and Clifton 1986; Trueswell et al. 1994). The expected reading times depending on word length were then subtracted from the original reading times leading to residual reading times. These residual reading times are either positive or negative depending on whether the word was read slower or faster than the expected word reading time for a word of that length. However, as the results of this analysis on the residual reading times were similar to the normal reading time results, only the first analysis is reported. Huynh–Feldt-corrected p-values are reported.

fMRI data acquisition

The fMRI data were acquired on a 3 Tesla Siemens Trio scanner. A functional T2* weighted EPI-BOLD fMRI scan was performed (TR = 3 s, TE = 35 ms), with a flip angle of 90°. We acquired 35 slices with a voxel size of 3.5 * 3.5 * 3.5 mm. The field of view was 224 * 224 mm for each slice. The slices were acquired in an interleaved manner in ascending order. The anatomical images were acquired using a T1 weighted GRAPPA sequence with a 1 * 1 * 1 mm resolution.

fMRI procedure

The stimuli were presented using Presentation software (Neurobehavioral Systems, www.neuro-bs.com). The general procedure was identical to the one in the behavioural experiment. Participants were lying the scanner and saw the stimuli via mirrors just above their head. In contrast to the behavioural experiment, the stimulus sentences were presented at a fixed presentation time of 350 ms per word. The length of the inter-stimulus interval between sentences during which a fixation cross was displayed was jittered between 1.5 and 4.5 s. Following 20% of the filler sentences a grammaticality decision had to be made by pressing one of two buttons.

Each participant saw only one of the eight stimulus lists. Each stimulus list was divided into four fMRI runs of 16 min. There was a short break between every run and the anatomical T1 images were acquired after half of the experiment.

fMRI data analysis

The fMRI data were preprocessed and analysed using SPM5 (Wellcome Neuroimaging Laboratory, London, UK). The first five image volumes were discarded to ensure that transient non-saturation effects did not affect the analysis. All volumes were slice-time corrected and realigned. The subjects' mean functional images were co-registered to the subjects' anatomical T1 images. The structural and functional images were anatomically normalized to a T1 template image. Finally, functional volumes were smoothed with an 8 mm FWHM Gaussian kernel.

The fMRI analysis was conducted in two steps. At the first level a single-subject analysis was conducted. The contrasts from the first level were then taken to the second level for a random effects group analysis.

The design matrix for each individual subject included regressors that modelled the sentence conditions from the third word onwards, the point in time where the sentence structure became apparent, to the final word in the sentence. There were four regressors modelling the experimental conditions of interest, English targets that were preceded by a German prime (GEP), English targets that were preceded by an English prime (EEP), English targets preceded by a German non-prime (GEU) and English targets preceded by an English non-prime (EUU). Moreover, we had sentence regressors that modelled the four types of primes and non-primes (GP, EP, GU, and EU) and the filler sentences in German and English (FILG, FILE). The first two words of all experimental and filler sentences were modelled together as a separate regressor (Wo). The consonant string sentences were modelled by a regressor from the third string as well (Con) and the first two strings were modelled as a separate regressor (WCon). Regressors were convolved with a hemodynamic response function with time derivatives. Furthermore, the realignment parameters for movement artefact correction were included in the design matrix.

Whole brain analysis

For this conventional whole brain analysis we generated single-subject contrast images for filler (FILE, FILG) and prime sentences (EP,
GP, EU, GU) combined relative to the consonant string sentences baseline (Con) in both English and German. This full factorial design allowed us to look at the factor Language with the two level German and English; as well as at the processing of sentences versus the baseline, a factor we will call Sentences.

Region of interest analysis

Repetition suppression effects were investigated in a more sensitive region of interest analysis (ROI). To detect repetition suppression effects in areas that are involved in sentence processing, we took the activation results from the main effect of sentences of the whole brain analysis as the functional region of interest. A region of interest analysis was then performed using the Marsbar toolbox for SPM ((Brett et al., 2002), http://marsbar.sourceforge.net), looking for the priming effects within the ROI with a $2 \times 2 \times 3$ ANOVA (Primed (primed; not primed) × Language combination (English–English; German–English) × Region (left middle temporal gyrus; left inferior frontal gyrus; left precentral gyrus)). This ANOVA was based on the contrast values (effects sizes for each region of interest), which were obtained from the single-subject contrast images for the priming conditions (GEP, EEP, GEU, EEU) with consonant string sentences (Con) as a baseline in the three regions.

Results

Behavioural experiment

Reading times

The information on which syntactic structure is presented becomes available from the third word onwards (see Fig. 1). As expected, the first two words of primed sentences were not read faster than those of unprimed ones, $F(1,15) = 0.028, p = 0.87, \eta^2_p = 0.00$ (see Table 4a). From the third word onwards primed English sentences were read faster than unprimed sentences, $F(1,15) = 13.86; p = 0.002,$ $\eta^2_p = 0.48$, irrespective of the language of the preceding sentence, thus there was no interaction with language combination (see Table 4b). There were no interactions with the factor word either showing a sustained priming effect from the third to the last word.

Grammaticality judgement task

The participants failed to respond to only 0.01% of the task stimuli (SD = 0.02). The hit rate, subjects correctly judging a sentence as being correct, was 88.62%. The false alarm rate was 23.1%. Therefore, one can assume that the participants generally attended to and processed the experimental stimuli.

fMRI experiment

Whole brain analysis

For this analysis we used a voxel-level threshold of 0.05 with family-wise error correction for multiple comparisons at a cluster threshold of 50. A main effect of sentences (the effect of reading sentences versus consonant string sentences) revealed increased activation in the left middle temporal gyrus, $t = 10.22, p < 0.001$, the left inferior frontal gyrus, $t = 8.29, p < 0.001$ and the left precentral gyrus, $t = 8.09, p < 0.001$ (see Table 5 and Fig. 2 for the exact activation locations). These regions were taken as the regions of interest in the subsequent region of interest analysis. The main effect of language did not reveal any activations, at a 0.001 uncorrected threshold level, indicating that there were no regions more active for English than for German and vice versa.

Region of interest analysis

The contrast values of the different conditions of the ROI analysis can be seen in Fig. 2. For all language combinations (German–English and English–German) and regions (left middle temporal gyrus; left inferior frontal gyrus; left precentral gyrus), the contrast value for the

Table 4

<table>
<thead>
<tr>
<th>Region</th>
<th>BA</th>
<th>Cluster size</th>
<th>Voxel T² value</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left middle temporal</td>
<td>22</td>
<td>267</td>
<td>10.22</td>
<td>−56</td>
<td>−42</td>
<td>2</td>
</tr>
<tr>
<td>left inferior frontal</td>
<td>44</td>
<td>101</td>
<td>8.29</td>
<td>−56</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>precentral gyrus</td>
<td>6</td>
<td>96</td>
<td>8.09</td>
<td>−52</td>
<td>2</td>
<td>48</td>
</tr>
</tbody>
</table>

Note: significant activation peaks >8 mm apart ($p < 0.05$ FWE corrected, $k = 50$). BA = Brodmann Area (according to the SPM Anatomy Toolbox, (Eickhoff et al., 2005)), $x$, $y$, $z$-coordinates are given in MNI space.

Table 4a

<table>
<thead>
<tr>
<th>Condition</th>
<th>Stimulus</th>
<th>Reading time (ms)</th>
<th>Confidence interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primed</td>
<td>English</td>
<td>382 (343–421)</td>
<td>384 (348–420)</td>
</tr>
<tr>
<td></td>
<td>German</td>
<td>385 (349–421)</td>
<td></td>
</tr>
<tr>
<td>Unprimed</td>
<td>English</td>
<td>382 (343–421)</td>
<td>384 (348–420)</td>
</tr>
<tr>
<td></td>
<td>German</td>
<td>385 (349–421)</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Behavioural priming effects. Reading times (in ms) of target sentences per word. (GEP: English targets preceded by a German prime; GEU: English targets preceded by an English non-prime). Primed target sentences are read faster from the third word onwards.

Table 5

<table>
<thead>
<tr>
<th>Region</th>
<th>BA</th>
<th>Cluster size</th>
<th>Voxel T² value</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left middle temporal</td>
<td>22</td>
<td>267</td>
<td>10.22</td>
<td>−56</td>
<td>−42</td>
<td>2</td>
</tr>
<tr>
<td>left inferior frontal</td>
<td>44</td>
<td>101</td>
<td>8.29</td>
<td>−56</td>
<td>18</td>
<td>24</td>
</tr>
<tr>
<td>precentral gyrus</td>
<td>6</td>
<td>96</td>
<td>8.09</td>
<td>−52</td>
<td>2</td>
<td>48</td>
</tr>
</tbody>
</table>

Note: significant activation peaks >8 mm apart ($p < 0.05$ FWE corrected, $k = 50$). BA = Brodmann Area (according to the SPM Anatomy Toolbox, (Eickhoff et al., 2005)), $x$, $y$, $z$-coordinates are given in MNI space.
primed sentences was lower than for the unprimed ones. The analysis revealed a significant main effect of prime, \( F(1,15) = 7.91, \ p < 0.05, \eta^2_p = 0.35 \). The mean contrast value for the primed condition was 8.53 (CI: 6.41–10.65), the one of the unprimed condition 10.31 (CI: 7.18–13.43). There was also a main effect of region, \( F(2,30) = 8.33, \ p < 0.05, \eta^2_p = 0.36 \) (mean contrast values lIFG: 12.43 (CI: 8.96–15.90), lMTG: 6.57 (CI: 4.64–8.51), lPrec: 9.25 (CI: 6.10–12.39)). None of the interactions reached significance. Thus, we find a general fMRI repetition effect for primed sentences that is statistically indistinguishable for the three regions and the two language combinations.

A whole brain analysis into the priming effect did not reveal a repetition effect or a significant interaction between the factors priming and language combination.

To exclude a possible contamination of the repetition suppression effect by the hemodynamic response to the preceding prime and non-prime sentences, we also conducted an analysis of the passive and active prime sentences in the three ROIs. An ANOVA with the factors sentence type (passive, active), language (English, German) and region (left middle temporal gyrus; left inferior frontal gyrus; left precentral gyrus) revealed a significant interaction between sentence type and region, \( F(2,30) = 10.19, \ p = 0.001, \eta^2_p = 0.40 \) (see Table 6).

Further analyses of the three different ROIs individually revealed no significant effects in the left inferior frontal gyrus and left middle temporal ROIs. Within the left precentral ROI passive sentences showed a higher level of activation than active sentences, \( F(1,15) = 6.56, \ p < 0.05, \eta^2_p = 0.30 \). Consequently, we can exclude that the repetition suppression effect we found above is due to a higher level of activation of the active no-primes compared to the passive primes carrying over to the target sentence.

**Grammaticality judgement task**

The participants failed to respond to only 0.005% of the task stimuli (SD = 0.7). The hit rate, subject correctly judging a sentence as being correct, was 91.26%. The false alarm rate was 29.1%. Therefore, one can assume that the participants generally attended to and processed the experimental stimuli.

**Discussion**

In this study we aimed at investigating the interaction between the first and second language syntactic systems. In a behavioural and an fMRI experiment we looked at priming and repetition suppression effects of syntactic repetition between the L1 and the L2 and within the L2. In both cases we included lexical overlap of the verbs, either in the form of translation equivalent verbs or actual verb repetition between prime and target. The behavioural experiment looked at modulations of reading time for primed target sentences from the third word onwards. Depending on the syntactic structure, the third word was either the main verb (active sentences) or an auxiliary verb (passive sentences) in both German and English. In the neuroimaging experiment, the approach was to first identify the areas active for processing sentences versus the baseline of sentence-format
consonant strings in a conventional whole brain analysis and then to look for repetition suppression effects within these areas. We found repetition suppression effects in three regions of interest in left inferior frontal, precentral and middle temporal cortex. In both experiments we did not find any interactions with the type of language combination, either L1 into L2 or within L2.

These findings provide us with clear evidence for shared syntactic systems between German (L1) and English (L2) on both the cognitive as well as the neural level.

**Syntactic priming**

Whereas syntactic priming is a well-replicated effect both in native language production and comprehension, evidence for syntactic priming within a second language is still scarce. As to our knowledge there are no previous data on cross-linguistic syntactic priming in comprehension, looking at the priming of two similar structures from two closely related Germanic languages is a first step. It complements recent findings in language production, e.g. a recent study into syntactic priming in L2 production for the dynamic alternation (Schoonbaert et al., 2007). Preliminary data on behavioural syntactic production priming between more distant languages (English and Korean) mentioned by Hartsuiker and Pickering (2008) suggests that our results might hold beyond typologically close languages. Our data complement the cross-linguistic syntactic priming in production findings by demonstrating that passive structures cannot only be primed in sentence comprehension for native speakers of English (Frazier et al., 1984) but also for learners of English. Although this result suggests that, at least in advanced L2 learners, first and second language syntactic processing may not rely on fundamentally different processing systems (Ullman, 2001) the crucial evidence for shared L1 and L2 syntactic processing systems can only be provided by demonstrating syntactic priming from one language to the other. Here we show that indeed the processing of English passive structures is primed by preceding German passive sentences even though the surface word order of passive sentences differs between the two languages. A study by Loebell and Bock (2003) in language production failed to find effects between these two languages. It is possible that the differences in word order in German and English passive structures might have had a stronger influence on a syntactic priming effect in production than in comprehension. In comprehension the target structure to be processed is fixed, while in production the participant can choose the structure to be produced. It is possible to prime surface word order alone (Bernolet et al., 2007; Hartsuiker et al., 1999; Hartsuiker and Westenberg, 2000). However, cross-linguistic syntactic priming effects can persist even with word-order differences (Desmet and Declerq, 2006). The results of the present study indicate that at least in comprehension a syntactic priming effect arises despite of word-order differences between the L1 and L2. This shows that in this case it is not merely the surface word order that is being primed (and thus shared between the L1 and L2) but some more abstract syntactic structure.

This behavioural cross-linguistic syntactic priming effect provides evidence for an interaction between the two syntactic processing systems. Accordingly, we can rule out that the two systems are completely separate. Moreover, we did not find an interaction of the priming effect with language combination that is the priming effect was statistically indistinguishable with and between languages. Following Hartsuiker and Pickering (2008), who argue that for separate but interacting processing systems between-language priming should be reduced compared to within-language priming, we interpret our finding of comparable within- and between-language syntactic priming effects as evidence for real overlap between the two syntactic systems.

In sum, our behavioural data are in accordance with the model by Hartsuiker and Pickering (2008) which predicts overlap between the first and second language syntactic systems. Correspondingly, neural substrates supporting syntactic processes should also be shared.

**L1 and L2 sentence processing in the brain**

At a general level, the results of our neuroimaging study are compatible with shared L1/L2 syntactic processing systems, because German (L1) and English (L2) sentences processing activated the same neural areas of left frontal and temporal regions with no differential activation for L1 or L2. These findings are in accordance with other neuroimaging studies on second language processing, which claim that essentially the same areas are used in processing the first and the second language (Chee et al., 1999; Luke et al., 2002; Perani et al., 1998; Suh et al., 2007; for reviews see Abutalebi, 2008; Abutalebi et al., 2001; Indefrey, 2006). Within this study we cannot exclude different results for different language pairs and we did not set out to look at distant language pairs. However, other results from e.g. Chee et al. (1999) on distant language pairs suggest that even in this case there are common neural substrates for L1 and L2 processing.

Note, however, that this finding per se does not constitute strong evidence for shared syntactic processing systems as we used a relatively low-level baseline condition (sentence-format consonant strings). This was done to define a set of regions-of-interest that are sensitive to sentence-level processes as well as to processes below the sentence level to capture lexically mediated as well as purely structural repetition suppression effects. As a consequence, our design does not provide an intrinsic constraint with respect to the functional interpretation of the resulting areas. Note however, that two of the three areas (left posterior middle temporal gyrus, left inferior frontal gyrus) have been linked to native language syntactic processing in several meta-analyses (Indefrey, 2004, to appear; Kaan and Swaab, 2002). We can, therefore, assume these ROIs to be appropriate for the detection of syntactic repetition suppression effects.

**Repetition suppression effects**

The observed repetition suppression effects suggest that left inferior frontal, precentral and middle temporal regions are involved in some aspect of syntactic processing as primed and unprimed target sentences differed with respect to the repetition of syntactic structure but not with respect to verb repetition. This finding confirms an earlier study reporting the existence of neural correlates of syntactic priming in comprehension (Noppeney and Price, 2004) but differs with respect to the anatomical location of the effects. Noppeney and Price (2004) found repetition suppression effects in the left anterior temporal pole, an area that has been connected to syntactic processing (Friederici, 2002) but was not among the regions of interest in our study because it did not show a significant activation increase for sentences versus sentence-format consonant strings. The syntactic structures of the sentences used in Noppeney and Price (2004) and in the present study were different and it is conceivable that the reduced relative clause sentences used in their study activate anterior temporal regions more strongly. One reason may be that anterior temporal regions are connected to processing the syntactic as well as the prosodic structure of a sentence (Humphries et al., 2005; Mazoyer et al., 1993). The local ambiguity of reduced relative clause versus main clause readings might be resolved by prosodic means because in the case of reduced relative clause sentences a prosodic break is present after the verb that is not present in the main clause sentences. Alternatively, it is possible that the syntactically simpler active, passive and filler sentences used in the present study did not engage all neural substrates of syntactic processing and hence we do not claim that our set of ROIs was all encompassing.

The focus of our study was the question of shared or different neural correlates of L1 and L2 syntactic processing. The observed between-language repetition suppression effects constitute strong
neural evidence for shared syntactic systems. This finding confirms previous evidence on overlapping brain activation for L1 and L2 sentence processing obtained with the subtraction paradigm. However, while shared activation of brain regions or even single voxels cannot exclude different neuronal populations being activated within these regions, the current finding shows that the same neuronal populations are responding to the processing of syntactic structures in either of the two languages.

In sum, the repetition suppression effect between languages confirms the behavioural findings and leads us to conclude that there is real overlap between the two syntactic systems of the first and second language. Moreover, the repetition suppression effect did not interact with the factor language combination. Thus, as the effect was statistically indistinguishable within and between languages, it is likely that the neuronal substrate involved in processing passive sentences is not only partially but fully shared. If the grammatical processing systems were only partially shared, within language priming would show a greater repetition suppression effect than priming between languages. In this case between-language priming would have only a subpopulation of neurons reacting to the processing of passive structures in both languages and thus a comparatively weaker effect. A different interpretation of such an interaction would be that there are actually two different grammatical representations, which are however linked closely and are thus interacting. However, our findings of no interaction with language combination indicate equal effects and thus shared representations. Another possible outcome would have been no priming or repetition suppression effects in the cross-linguistic condition. This would have either meant that we did not use a good paradigm to test for interactions between L1 and L2 or that there is no interaction between the two grammatical systems.

In sum, our finding of cross-linguistic syntactic priming and repetition suppression indicates that functional and neural representations of similar syntactic structures, like the passive can be shared by L1 and L2. One consequence of this result may be that learning a L2 syntactic structure for which an existing L1 representation can be used should be facilitated and place fewer demands on the brain regions involved.

Structural versus lexically mediated priming

Behaviourally, the syntactic priming effect appears to be present even before the verb. Consequently, we can assume a structural component to the effect. From the verb onwards however, we cannot distinguish between a purely structural and a lexically mediated effect. In production, Pickering and Hartsuiker (Hartsuiker et al., 2004; Schoonbaert et al., 2007) extended the verb-subcategorisation frame hypothesis by Pickering and Branigan (1998) into a theory on bilingual language processing. In this model the lexicon is shared between L1 and L2 and combinatorial nodes which code for example for passive or active structures are linked to all L1 and L2 verbs that can build sentences with these structures. The priming effect is then due to the preactivation of a combinatorial node by the processing of the prime sentence. Thus, this model can account for structural priming effects as well as the lexical boost in cross-linguistic production studies. Based on our data it seems feasible to extend this model to sentence comprehension. However, we are not yet able to decide altogether whether structural priming effects entirely independent of verb repetition are possible in sentence comprehension as all our trials contained verb repetition. Previous studies (Arai et al., 2007; Branigan et al., 2005; Ledoux et al., 2007; Tooleey et al., 2009) made a strong case for verb repetition being essential in syntactic priming in comprehension, whereas only a few studies found syntactic priming in comprehension without verb repetition (Noppeney and Price, 2004; Thothathiri and Snedeker, 2008). Our data showed no statistical difference between the priming and repetition suppression effects for sentences with repeated identical verbs (within-language) and repeated translation-equivalent verbs (between-languages). Future studies will have to look into the role of verb repetition in comprehension more closely to elucidate the nature of syntactic priming in sentence comprehension.

Conclusion

The results of the present experiment indicate that syntactic priming effects in comprehension for passive structures can be detected within the L2 and from L1 to L2. Both the behavioural and the neuroimaging results favour the idea of an overlapping syntactic system as comparable syntactic priming and repetition suppression effects were observed within and between languages.

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References


