TITLE: "Anatomical and functional changes in the brain after simultaneous interpreting training: A longitudinal study."

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ABSTRACT

In the recent literature on bilingualism, a lively debate has arisen about the long-term effects of bilingualism on cognition and the brain. These studies yield inconsistent results, in part because they rely on comparisons between bilingual and monolingual control groups that may also differ on other variables. In the present neuroimaging study, we adopted a longitudinal design, assessing the long-term anatomical and cognitive effects of an extreme form of bilingualism, namely simultaneous interpreting. We compared a group of students starting interpreting training with a closely matched group of translators, before and after nine months of training. We assessed behavioral performance and neural activity during cognitive control tasks, as well as the structural connectivity between brain regions that are involved in cognitive control. Despite the lack of behavioral differences between the two groups over time, functional and structural neural differences did arise. At the functional level, interpreters showed an increase of activation in the right angular gyrus and the left superior temporal gyrus in two non-verbal cognitive control tasks (the Simon task and a colour-shape switch task), relative to the translators. At the structural level, we identified a significant increment of the structural connectivity in two different subnetworks specifically for the interpreters. The first network, the frontal-basal ganglia subnetwork, has been related to domain-general and language-specific cognitive control. The second subnetwork, in which the cerebellum and the SMA play a key role, has recently also been proposed as an important language control network.

These results suggest that interpreters undergo plastic changes in specific control-related brain networks to handle the extreme language control that takes place during interpreter training.

INTRODUCTION

Recently, a lively discussion originated both in the scientific and popular literature about the broad effects of multilingualism on general cognition and functioning of the brain. Many recent studies have focused on the relationship between the two, and found that speaking more than one language positively affects cognitive control and problem-solving (e.g. Bialystok & Majumder, 1998; Bialystok, Martin, & Viswanathan, 2005; Costa, Hernández, & Sebastián-Gallés, 2008; Woumans, Surmont, Struys, & Duyck, 2016). This finding is typically termed the 'bilingual advantage' and suggests enhanced cognitive processing in bilinguals compared to monolinguals. It is believed that this enhanced processing is the result of constantly having to juggle two or more languages. Studies on bilingual lexical access have indeed demonstrated that a bilingual's languages are simultaneously activated and interacting at all times (Colomé & Miozzo, 2010; Duyck, 2005; Van Assche, Duyck, Hartsuiker, & Diependaele, 2009; Van Hell & Dijkstra, 2002). A possible mechanism to handle this simultaneous activation was proposed by Green (1998) in his Inhibitory Control (IC) model. This model for language control suggests that bilinguals activate one language for production and inhibit the other. This process is thought to be domain-general and not language specific, implying that training the mechanism by continually activating one language and inhibiting the other may also improve other types of cognitive control.

However, whereas some labs have consistently replicated bilingual advantages (e.g. Bialystok, Craik, Klein, & Viswanathan, 2004; Bialystok, 2006; Bialystok & Feng, 2009), leading to a significant bilingual advantage effect in the meta-analysis of de Bruin, Treccani and Della Sala (2015), the same meta-analysis also showed a publication bias for positive results. Similarly, Paap and Greenberg (2013) and Paap, Johnson, and Sawi (2014) claimed that a large majority of studies, up to 85%, did not show a bilingual advantage. The controversy even led to a special issue of *Cortex* (Paap, Johnson, & Sawi, 2015) devoted to this particular discussion. In this issue, Woumans and Duyck (2015) argued that the literature should move away from the yes/no discussion, and instead focus on the possible moderating factors that seem crucial for the bilingual advantage to occur.

There is empirical evidence that one of those possible moderators may be

(extensive) language switching. Prior and Gollan (2011), for example, revealed that frequent language switchers outperformed non-frequent language switchers and monolinguals on a non-verbal switching task. By contrast, the non-frequent switchers did not show any task switching advantage relative to the monolinguals. Verreyt, Woumans, Vandelanotte, Szmalec, and Duyck (2016) confirmed these findings in two conflict resolution tasks: the flanker task (Erisken & Eriksen, 1974) and the Simon task (Simon & Rudell, 1967). The authors compared two groups of highly proficient bilinguals (frequent and non-frequent switchers) and a group of low proficient bilinguals. They only found cognitive advantages for the frequent language switchers and concluded that frequent language switching, rather than mere second language (L2) proficiency is key to developing improved cognitive processes. In addition, Woumans, Ceuleers, Van der Linden, Szmalec, and Duyck (2015), reported a positive correlation between an experimental measure of language switching proficiency in a verbal fluency task on the one hand and conflict resolution in the Simon task on the other hand. Taken together, these results suggest that not merely being a bilingual may lead to better cognitive control, but rather that specific practice in language control (among other possible factors) may be crucial. On the other hand, such moderating effects may be quite complex, given that other studies like those of Paap et al. (2015), Paap et al. (2017) and Yim and Bialystok (2012) failed to find similar effects of language switching experience.

An interesting line of research that is closely related to this notion of switching as the determining factor in the bilingual advantage debate is what happens in bilinguals that need to use extreme language control, namely simultaneous interpreters. Simultaneous Interpreting (SI) requires concurrent comprehension of a spoken message in the source language (SL) and reformulation of the message into the target language (TL), while at the same time producing a previously transformed source message in the target language (Chernov, 1994). Therefore it is obvious that high-level language control is necessary to manage this extremely challenging task. Through all these simultaneous processes, requiring different languages to a different extent, simultaneous interpreters manage greater levels of language control in comparison to other bilinguals, which in turn may lead to greater cognitive gains.

At the behavioral level, different studies have investigated the cognitive benefits

of SI experience. Interpreters typically receive special training to improve working memory, which encouraged some researchers to focus on this aspect and report superior working memory in interpreters compared to other bilinguals (Christoffels, de Groot, & Kroll, 2006; Köpke & Nespoulous, 2006; Padilla, Bajo, & Macizo, 2005).

Others have taken into account more general cognitive processes, looking at the performance of SI on different cognitive control tasks, following the same rationale of transfer from language control to domain-general cognitive control.

The effect of SI on measures of inhibition is an unresolved issue that requires further research to resolve the contradictory findings in previous research. Some researchers have failed to find many differences between SI and other multilinguals on tasks relying on inhibition (Babcock & Vallesi, 2017; Dong & Xie, 1014; Morales, Padilla, Gómez-Ariza, & Bajo, 2015; Yudes, Macizo, & Bajo, 2011), while others did report some interpreter advantage for inhibitory skills (Dong & Zhong, 2017 & Woumans et al., 2015).

In contrast, studies employing cognitive flexibility measures have disclosed more consistent evidence for a SI advantage. In the study by Yudes et al. (2011), SIs outperformed both monolinguals and bilinguals on the Wisconsin Card Sorting Test (WCST). Both Becker, Schubert, Strobach, Gallinat, and Kühn (2016) and Babcock and Vallesi (2017) employed a color-shape task shifting paradigm and compared groups of professional SIs to other multilinguals, one of which was actually a group of consecutive interpreters, who were trained to first listen to the source text and only afterwards, with the aid of notes, make a full rendition. Still, SI seemed to outperform all other groups on a measure called 'mix cost'. This was calculated by comparing performance on all trials in a blocked condition where there is no possibility of a task switch with performance on repeat trials in a switch condition, where there is the possibility of a task switch but it did not occur. Hence, SIs seem to have obtained a higher level of automatic or sustained control, which comprises keeping multiple task sets activated and engaging attentional monitoring processes to increase sensitivity to cues that signal task changes (Funes, Lupiáñez, & Humphreys, 2010). However, no differences were reported for 'switch cost', which indexes transient control, by comparing performance on repeat and switch trials in a switch condition. This transient control entails internal reconfiguration or updating of

goals and linking task cues to their appropriate stimulus-response mappings.

One issue however with these SI studies (as well as with studies on the bilingual advantage) is that most of them necessarily compare cognitive functioning between groups, that differ in SI experience, but that may also differ on other untargeted variables. To answer the question of causality and ensure that SIs are not predisposed to cognitive superiority, only a few studies have employed longitudinal designs, within participants. For instance, Macnamara & Conway (2014) followed a group of American Sign Language interpreting students over the course of their two-year training and found that over time, they demonstrated increased fluency in both mental flexibility and task shifting. There was, however, no control group. In another longitudinal design, Dong and Liu (2016) looked into inhibition, shifting, and updating gains in students of consecutive interpreting, written translation, and a general English course. After six months of training, consecutive interpreters displayed progress on both shifting and updating, whereas the translators only marginally improved on updating and the English students showed no progress at all. In contrast, Babcock, Capizzi, Arbula and Vallesi (2017) who also used a longitudinal design with a matched control group of translators, showed no effects of SI training on the performance of two executive control tasks: the Attention Network Task (ANT) that taps into inhibition, and a switch task. They only revealed an SI advantage in a verbal short memory task.

To complement the behavioral research, neuroimaging research has focused on neural plasticity as a consequence of SI. Elmer, Hänggi, and Jäncke (2014a) and Elmer, Hänggi, Meyer, and Jäncke (2011a) investigated structural brain differences associated with SI, using a cross-sectional design. Elmer et al. (2011a) examined the structural networks with DTI in predefined brain regions involved in the mapping of sounds to articulation, the motor control of speech, and interhemispheric transfer. They reported significant lower fractional anisotropy (FA) in the networks that subserve sound to motor mapping for the group of graduated SIs, compared to a multilingual control group. In the same group of participants as in the study of Elmer et al. (2011), Elmer et al. (2014) compared the gray matter volumes between the SI and multilingual control subjects, uncovering a structural difference in a priori defined brain regions that were previously shown to be involved in language control and linguistic functions. More specifically, this

study demonstrated reduced gray matter volumes for professional SIs, in the left middle-anterior cingulate gyrus, bilateral pars triangularis, left pars opercularis, bilateral middle part of the insula, and in the left supra-marginal gyrus (SMG). Note, however that the between-group comparison implied an age difference (age was higher in the SI group than in the control group) that may confound anatomical differences.

In addition to structural brain differences, Elmer, Meyer, Marrama, and Jäncke (2011b); Hervais-Adelman, Moser-Mercer, and Golestani (2015); and Hervais-Adelman, Moser-Mercer, Michel, and Golestani (2015) investigated functional brain differences associated with SI. Elmer et al. (2011b) conducted a cross-sectional study on functional differences between 10 professional SIs and 16 equally educated, but younger controls during a non-verbal auditory discrimination task that relies on attention and categorization functions. The results revealed functional differences in fronto-parietal regions between the two groups, despite the absence of behavioral differences. They concluded that intensive language training modulates the brain activity in regions that are involved in the top-down regulation of auditory functions. However, due to an age difference between the two groups, these results should again be interpreted with care.

Hervais-Adelman et al. (2015b) compared the functional involvement of brain regions during SI with the involvement of brain regions during simultaneous repetition (i.e. shadowing - SH). Participants were 50 multilinguals without previous SI experience. This comparison revealed that the caudate nucleus, the left anterior superior motor area (SMA), pre-SMA, the left anterior insula, the left premotor cortex, the right cerebellum, the left inferior frontal gyrus, and the dorsal anterior cingulate cortex (ACC) are more activated during SI than during SH. Hervais-Adelman et al. (2015a) opted for a longitudinal design examining brain plasticity as a result of intensive SI training. Nineteen trainee interpreters and 16 multi-lingual control participants were scanned at the beginning and at the end of the fifteen months intensive training course. The multilingual controls were students in non-linguistic fields who reported to have an equal degree of language proficiency in the same number of languages. The authors reported reduced involvement of the caudate nucleus during the SI task after fifteen months of training in the interpreters. The recruitment of the caudate nucleus in both studies, and especially the longitudinally induced brain plasticity in the caudate nucleus after intensive SI training,

highlights the role of the caudate nucleus in SI. This region is also known to be implicated in domain-general cognitive control (Aron et al., 2007; Atallah, Frank, & Reilly, 2004).

All these neural SI studies focused on linguistic tasks rather than cognitive control tasks, which are typically used in the behavioral literature to investigate the cognitive benefits of SI, and in the more general literature about the bilingual advantage. One exception is Becker, Schubert, Strobach, Gallinat, and Kühn (2016) who investigated both functional and structural brain differences related to SI experience within a cross sectional design. Their results revealed that SI showed less mixing costs in a (non-linguistic) color-shape switch task, performed better in a (non-linguistic) dual task paradigm and showed more gray matter volume in the left frontal pole than translators.

Still, up until now, there were no studies investigating the influence of SI experience on cognitive control tasks instead of linguistic tasks, using a well-controlled behavioral and neural longitudinal design that manipulated SI experience within subjects. Hence, in the present study, we compared two matched groups of multilinguals, one of which was about to commence SI training and the other starting a translation course. We opted for this very conservative comparison of two very similar training programs (SI versus translation), organized by the same higher education institution, in order to identify the cognitive and neural changes specifically related to SI. We followed the two groups that had been enrolled in the exact same Bachelor program in Applied Linguistics until the start of follow-up, over a period of nine months. As such, this is the first study to examine longitudinal changes as a result of SI training, both in behavioral performance, using non-linguistic cognitive control tasks, as well as on a neural level, measuring both structural connectivity and functional differences.

On the basis of previous research our expectation was that, due to the extreme language control, SIs would outperform translators on an inhibitory control task (Dong & Zhong, 2017; Woumans et al., 2015) and on a switch task (Becker et al., 2016; Babcock & Vallesi, 2017), that they would show different levels of neural activation during these tasks, and would show altered connectivity between brain regions that typically subserve domain general cognitive control (Becker et al., 2016).

We chose an inhibition task and a switch task, because these tasks are typically

put forward to engage the core functions underlying SI, namely inhibitory control and flexibility (Christoffels & de Groot, 2005; de Groot & Christoffels, 2006; Hiltunen et al., 2016; Pöchhacker, 2004). As specific measures of these functions, we particularly chose the Simon task as the inhibition task and the colour-shape switch task as the switch task, because these tasks are most often used in the literature about the bilingual advantage (e.g. see the bilingual advantage meta-analysis of de Bruin et al., 2015), next to the flanker task. Interestingly, the Simon task and the colour-shape switch task were not only used in the bilingual advantage literature but also in previous research on the effect of SI experience (Babcock & Vallesi, 2017; Becker et al., 2016; Woumans et al., 2015; Yudes et al., 2011). For the colour-shape switch task, Becker et al. (2016) and Babcock and Vallesi (2017) found that SI's outperformed other multi-linguals on the mix cost, but not on the switch cost. In contrast, Babcock et al. (2017) didn't find an SI advantage on the mix cost either. On the Simon task, Woumans et al. (2015) and Yudes et al. (2011) showed that SI's didn't outperform other bilinguals despite the idea that inhibitory control plays a crucial role during SI (Christoffels & de Groot, 2005; de Groot & Christoffels, 2006)."

We additionally investigated the performance on, and neural activation during, a language switch task as a linguistic verbal control task, because language switching is proposed as one of the possible moderators that can shape the brain regions on which domain general cognitive control relies (De Baene, Duyck, Brass, & Carreiras, 2015). This also allowed relating the present study to the neuroimaging literature discussed above, which also focused on linguistic tasks.

METHOD

Participants

Eighteen right-handed trainee simultaneous interpreters (4 males, 14 females) with an average age of 21.4 years (range 21-23) and eighteen right-handed trainee translators (6 males, 12 females) with an average age of 21.9 years (range 21-26) participated in the study. All participants were scanned before and after a nine-month Master course SI or translating. Four additional participants were excluded, as they were unable to participate in the second round of data-collection. After each scan session, participants received a compensation of €35. Up until the first moment of testing, both translators and SIs had been enrolled in the same three-year Bachelor program in Applied Linguistics. Only in this final Master year, students had to chose between SI and translator training. In the SI training, all courses and an internship were aimed at developing students' interpreting skills for their two chosen foreign languages. The same was the case for the translating training, in which the courses and internship were aimed at developing student's written translation skills for two foreign languages (see Table 1 for an overview of the distribution of the different language pairs). The two groups were comparable on factors such as socioeconomic status (SES), gender, second language (L2) proficiency, and age of L2 acquisition (L2 AoA). Within this design, other differences than the interpreting training itself were excluded. All participants had Dutch as their first language (L1). They reported a high level of proficiency in at least two other languages (see Table 2 for an overview of the demographic data).

Materials and Procedure

A longitudinal design with both fMRI and DTI was employed to investigate, respectively, functional changes and structural connectivity changes in the brain. These were administered before and after 9 months of translator or SI training, so that neural changes could be observed within-subjects, for both groups. During the functional scans, participants completed two non-verbal cognitive control tasks (a color-shape switch task and a Simon task) and one language switching task (verbal fluency task). First, they did

the color-shape switch task, followed by the verbal fluency task and the Simon task. Finally, the scan session ended with the DTI-scan, during which participants were asked to lay still and do nothing.

Simon task

      We used a color version of the Simon task as a non-verbal cognitive control measure, which requires inhibition of irrelevant information and the response associated with it. The Simon task is commonly used in the literature on the bilingual advantage (e.g. Woumans et al., 2015). It primarily taps into inhibitory S-R processes, unlike for instance Stroop tasks that are more focused on S-S competition (Blumenfeld & Marian, 2014).

      In the Simon task, a green or red dot appeared on the left or right side of the visual field. Participants responded to the color of the dot with the left or right index finger, while ignoring its location on screen. Response mapping was counterbalanced over participants. Each trial began with a fixation screen, with a fixation cross presented in the center for 500 ms. Then, a blank screen appeared for 500 ms followed by a green or red dot on the left or right side of the visual field with a maximum response time of 1500 ms. Only if an incorrect response was given, a red feedback screen appeared for 200 ms. We used a jittered blank intertrial interval screen (mean = 3345.27; range = 2200-5320 ms; distributed with pseudologarithmic density).

      In the test block, each possible combination of position and color was presented 16 times, resulting in one run of 64 trials. Half of the trials were congruent and the other half were incongruent. On congruent trials, location of the stimulus on screen corresponded to the side of the button participants had to press as response to the color. On incongruent trials, location of the stimulus on screen and color of the dot elicited different responses. Before the test block, a practice block of eight trials was applied to make sure that the participants understood the task. An event-related approach was used for the Simon task. More specific, we analyzed the congruency effect as the difference in performance between incongruent and congruent trials (Yudes et al., 2011). This was used as measure of conflict resolution skills (i.e. the congruency or Simon effect). The total duration of this task was approximately 15 minutes.

Color-shape switch task

A color-shape switch task was employed as a second non-verbal cognitive control measure (Prior & Gollan, 2011). In this task, participants judged the color and shape of blue or yellow triangles and squares. They responded with the right or left index and middle finger to the shape or color of the target. Response mapping for both tasks (color and shape) to the right or left side of the hand was counterbalanced across participants. The task consisted of four runs. The experiment started with two single task blocks, in which participants judged either the color or shape of the target, followed by two mixed-task blocks in which they had to alternate between both tasks depending on the cue they were given (when a rainbow is shown, they need to perform the color task, when a geometrical figure is shown they have the perform the shape task. The order of the single task blocks (color-shape or shape-color) was also counterbalanced across participants.

Each trial started with a 600 ms fixation cross. In the single task blocks, the target then directly appeared in the center of the screen and remained on screen until the participant responded or for a maximum duration of 2500 ms. Next, a blank interval screen was presented for 300 ms before the onset of the following trial. In the mixed-task blocks, a task cue additionally preceded the target for 400 ms. The cue for the color task was a rainbow circle and for the shape task, it was a geometrical octagram. The single task blocks included eight practice trials, followed by 36 experimental trials. The two mixed-task blocks were preceded by ten practice trials and included 47 experimental trials each. Twenty trials were switch trials and 27 trials were repeat trials with a maximum of four consecutive repetitions. Before each block, an instruction screen was shown until the participant pushed a button to continue. In previous studies an equal amount of switch/repeat trials was often used (Prior & Gollan, 2017), however previous studies also showed that the sensitivity of the switch cost increases with lower switch probabilities (Duthoo, De Baene, Wühr, & Notebaert, 2012; Mayr, 2006; Monsell & Mizon, 2006; Schneider & Logan, 2006). Because one of our main aims was to assess a possible interaction between (SI vs. control) groups and switching, we opted for a colour-shape switch design with less switch trials, compared to repeat trials, in order to maximize the switch sensitivity.

As in previous studies, both the mix and switch cost were used as dependent variables (Babcock & Vallesi, 2017). The mix cost is the difference between performance on repeat trials in the mixed-task blocks compared to performance on all trials in the single task blocks, whereas the switch cost is the difference between performance on repeat trials and performance on switch trials within the mixed-task blocks. This event-related approach was however only used to analyze the behavioral data. As a consequence of the temporal resolution of fMRI, we couldn't dissociate brain activation for switch and repeat trials that occur quickly and interchangeably. To compensate for this we used a blocked approach instead of an event related approach to look both at the transient switch cost and the mixing cost. More specific, we chose for a contrast between mixed and single task blocks, because this measures both the neural correlates of the transient switch cost and the mixing cost, while at the same time keeping the power as high as possible, despite the limited amount of trials (Babcock & Vallesi, 2017). The total duration of this experiment was approximately 17 minutes.

Verbal fluency task

As a verbal switching performance measure, semantic fluency was assessed. The task consisted of one run, including three experimental blocks of one minute each. During each block, participants had to produce as many names of animals as possible in one minute while a fixation screen was shown. The first two blocks were single language blocks, in which they had to respond in either L1 or L2. The third block was a mixed-language block, in which they had to alternate between both languages. Each block was preceded by an instruction screen with a duration of 8000 ms. A switch cost was calculated by subtracting the number of words produced in the mixed-language condition form those produced in the single language conditions. The total duration of this experiment was approximately 5 minutes.

Data acquisition

Functional scans were acquired using a 3T whole-body Magnetom Trio MRI scanner with a standard 32-channel radio-frequency head coil (Siemens Medical Systems, Erlangen, Germany). To avoid motion artefacts, head fixation pillows were used and the participants were instructed not to move their head during the whole scan session. As required for anatomical localization, each session started with a high-resolution 3D structural scan, using a T1-weighted 3D MPRAGE sequence (TR = 2250 ms, TE = 4.18 ms, TI = 900 ms, acquisition matrix = 256 x 256 x 176, FOV = 256 mm, flip angle = 9˚, voxels resized to 1 x 1 x 1 mm). Next, whole brain functional images were acquired using a T2*-weighted EPI sequence, sensitive to blood oxygen level-dependent (BOLD) contrast (TR = 2000 ms, TE = 28 ms, image matrix = 64 x 64, FOV = 224 mm, flip angle = 80˚, slice thickness = 3 mm, distance factor = 17%, voxels resized to 3 x 3 x 3 mm, 34 axial slices). A varying number of images were acquired per run in the Simon task and the Color-shape switch task as a consequence of the self-paced initiation of the trial. In the verbal fluency, task a fixed number of images (119) were acquired per run.

The experimental tasks in which the participants had to respond to visual stimuli were projected on a screen with a video projector. This screen was visible for the participants through mirror glasses. Two button devices that each consisted out of two buttons were given to the participants. The required buttons depended on the specific task.

DW-MRI was acquired using a single-shot spin echo-planar imaging (EPI) sequence, with 64 gradient directions at b-value = 1200 s/mm2 and 1 unweighted (b = 0) image. Echo time (ET) = 83 ms, repetition time (RT) = 10800 ms, FOV = 240 ×240mm2, matrix size 96 × 96, 60 contiguous slices and an isotropic voxel resolution = 2.5 × 2.5 × 2.5 mm were applied as parameters. The total scan time for the DW-MRI protocol was approximately 14 min.

fMRI analysis

Pre-processing

The acquired fMRI-data were processed and analysed using SPM8 software (Wellcome Department of Cognitive Neurology, London, UK). The first four volumes of each run were excluded from the analysis to reach signal equilibrium. The functional images were corrected for slice timing and were spatially realigned to their mean image by rigid body transformation. To ensure an anatomically-based normalization, this functional mean image was co-registered with the high-resolution structural image and normalized to the Montreal Neurological Institute (MNI) template. Next, the functional images were smoothed with an 8 mm full-width half-maximum (FWHM) Gaussian kernel. Additionally, a high-pass filter with a cut-off of 128 s was used to remove low-frequency noise in the time series data at each voxel.

1st level analysis

Statistical analyses were performed on the data of the individual subjects by adopting the general linear model (GLM) in SPM8. In the Simon task, the fMRI time series data were modelled by two vectors reflecting the congruency of the trial (incongruent vs. congruent). These two vectors were convolved with the canonical hemodynamic response function (HRF) and entered into the regression model (the design matrix). For the verbal fluency task and the color-shape switch task, analyses were done within a blocked design. The predictor variables in the design matrix were composed of epochs representing the different conditions. Each epoch was convolved with a canonical HRF.

For every task, contrast images of interest were defined and created for every subject (contrast Simon task: incongruent > congruent, contrast color-shape switch task: task mix > task A & task B, contrast verbal fluency task: language mix > L1 & L2).

Whole brain, voxel-by-voxel second-level statistical analyses were performed to see whether significant differences were found between the two groups in the increase or decrease over time of brain activation recruited by the three fMRI tasks. For each task, the resulting first-level contrast images from the single subject analyses were submitted to a second level flexible factorial design with time (Time1 vs Time2) and group (SI vs translators) as factors. Group map significance was defined using a threshold of $p < .005$ at voxel level and an uncorrected cluster level for the whole brain at $p < .05$. We performed an interaction analysis between the group and time to test whether SI differ from translators over time. We opted for whole brain t-tests to better understand the directionality of the results.

Structural Connectivity analysis

For this analysis, we followed the same procedure used by García-Pentón et al. (2014).

Pre-processing

The acquired DW-MRI data was pre-processed using FMRIB's Diffusion Toolbox (FDT; Smith et al., 2004) as part of FSL 5.0.2 software package (available at http://www.fmrib.ox.ac.uk/fsl/). To correct for the distortions induced by the diffusion encoding gradients and distortions induced by head motion, Eddy currents correction was applied using affine registration to the $b = 0$ image (first volume in the dataset). Next, individual diffusion parameters were estimated in each voxel by fitting a tensor model to the raw diffusion data, resulting in fractional anisotropy (FA) images.

For each participant, the T1-weighted images were co-registered to the b0 images and segmented in 3 tissue probability maps: grey matter (GM), white matter (WM) and cerebrospinal fluid (CSF) using the SPM8 software package (http://www.fil.ion.ucl.ac.uk/spm/). Using these three tissue classes and the matrix transformation to MNI space obtained from the segmentation, the cerebral cortex of each participant was automatically parcellated into 115 GM regions taken from the AAL atlas (Tzourio-Mazoyer et al., 2002). This was done with the IBASPM toolbox

(http://www.fil.ion.ucl.ac.uk/spm/ext/#IBASPM;   Alemán-Gómez,   Melie-García,   &
Valdés-Hernández, 2006). Next, to create the seed points mask needed for the
tractography, the individual atlases in T1 native space were resliced to DTI space using
the nearest-neighbour interpolation in SPM8.

1st level analysis: White matter tractography

For each participant, the voxel-region connectivity was determined with the
probabilistic fiber tractography algorithm implemented in the FSL software (Behrens et
al., 2003). This algorithm calculates the axonal connectivity values between each brain
voxel and the surface of each of the 115 GM regions. The connectivity values are
estimated by calculating the number of generated paths that passed through the brain
voxels from the seed region. As tracking parameters we used 5000 paths from each seed
point (defaults in the FSL software package as optimum to reach the convergence of the
algorithm), 0.5 mm as step length, 500 mm maximum trace length, and a curvature
threshold of ±80º.

Next, the whole-brain undirected weighted network was created for each
participant. Each of the 115 AAL-based grey matter regions was represented by nodes.
When the connectivity value between the boundary voxels of two regions i and j was
different from zero, an undirected arc a_{ij} between the nodes i and j was established.
Additionally, the arc weights $w(a_{ij})$ were calculated based on the connectivity values
between regions i and j (Iturria-Medina et al., 2011). This was done by counting the
'effective' number of voxels over the surface of both regions and weighting each voxel
by its voxel-region connectivity value with the opposite zone, relative to the total number
of considered superficial voxels.

2nd level analysis: Network-based statistic (NBS) analysis

The NBS approach is generally used to perform a non-parametric statistical analysis to
identify components (connected structures) that are formed by a set of links (connections)
between regions that exceed an appropriately chosen supra-threshold link (Zalesky et al.,
2010a). In the subsequent GLM analysis, a 2 x 2 way ANOVA with one between-subject
factor (Group: SIs vs. Translators) and one within-subject factor (Time: Time1 vs.

Time2) was applied to isolate the components of the 115×115 undirected connectivity matrices that differ significantly between the two groups over time. A component (sub-network) is defined as a set of interconnected edges (i.e. links between GM regions) in the connectivity matrix.

Within the NBS analysis, we first tested the null hypothesis (H0) that the values of connectivity between the two populations come from distributions with equal means. This was done with a two sample T-test that was performed independently at each edge of the connectivity matrix.

To identify the set of supra-threshold edges a T-value of 3 was used as threshold for the statistical values of each edge of the connectivity matrix. All components (formed by interconnected supra-threshold edges at which the H0 was rejected) were identified and there size was estimated. A non-parametric permutation test, consisting out of 10000 independent randomly generated permutations was used to estimate the significance of each component. The group (SIs vs translators) to which each subject belongs was randomly exchanged and the statistical test was then recalculated for each permutation. Next, the same threshold (T-value = 3) was applied to create the set of supra-threshold links for each permutation. Then, the size (number of edges that the components comprise) of the largest component in the set of supra-threshold links of each permutation was used as an empirical estimation of the null distribution of the maximal component size.

Finally, an FWE corrected p-value was assigned to each connected component, based on its size. Therefore, the p-value of each observed connected component was corrected by calculating the proportion of permutations for which the maximal component size was greater than the observed connected component size, normalized by the number of permutations (i.e. 10000) (For more details see Zalesky et al., 2010a. For applications and examples of the NBS approach see Bai et al., 2012; García-Pentón et al., 2014; Verstraete et al., 2011; Zalesky et al., 2010b).

RESULTS

Behavioral data

The behavioral data was analyzed with SPSS 24 (Table 3). A GLM 2x2 mixed design ANOVA (2x2) was used to compare the performance between the two groups over time, with a within-subjects factor time (two levels: Time 1 vs. Time 2) and a between-subjects factor group (two levels: SIs vs. Translators). For the Simon task, the Simon effect (incongruent - congruent) of the reaction times (RT's) and the response accuracies were used as dependent variables. For the color shape switch task, the switch cost (switch trials in the mixed-task blocks - repeat trials in the mixed blocks) and the mix cost (repeat trials in the mixed blocks - all trials in the single blocks) of the reaction times and the accuracies were used as dependent variables. For the verbal fluency task, the dependent variable was the number of produced words. Participants with a total accuracy of less than 60% were excluded in the color-shape switch task, so that 32 out of 36 participants were retained. From the 4 excluded participants, 1 followed the SI program and 3 followed the translator program. In the Simon task, all 36 participants remained in the analysis. The individual RTs that exceeded 2.5 SD of the mean RT across all trials were excluded. This procedure eliminated 3.8% of all Simon data and 7.9% of all switch data.

For the verbal fluency task, we performed our analyses on the data of 25 participants, as the sound recordings of the other participants were disturbed through the scanner noise. From the 11 excluded participants, 6 followed the SI program and 5 followed the translator program.

Simon task[1]. In the RT analysis of the Simon cost (RT incongruent - RT congruent), the main effects of Time ($F(1,34) = 1.29$, $p > .26$) and Group ($F<1$) were not significant, nor was the interaction effect of Time and Group ($F(1,34) = 2.91$, $p = .097$). In the accuracy analysis of the Simon cost (ACC congruent - ACC congruent), the main

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[1] If we added congruency as a factor to our ANOVA, using plain RTs as the dependent variable, we observed a typical Simon effect, with significantly faster RT's for the congruent trials than incongruent trials ($F(1,34) = 68.63$, $p < .001$). The interaction of time x group x congruency was however not significant ($F(1,34) = 2.91$, $p = .097$), which also confirms that changes in the Simon effect over time were not significantly different for both groups.

effect of Time ($F<1$) and Group ($F<1$) were not significant and also no significant Time*Group interaction was found ($F(1,34) = 3.02, p = .091$).

Color-shape switch task[2]. In the mix cost RT analyses (RT repeat trials in the mixed blocks - RT all trials in the single blocks), we found no main effect of Time ($F<1$) or Group ($F<1$). The interaction between Time and Group was also not significant ($F(1,30) = 1.65, p > .20$). In the switch cost RT analyses (RT switch trials in the mixed-task blocks - RT repeat trials in the mixed blocks), neither a main effect of Time ($F(1,30) = 1.14, p > .29$) nor of Group ($F<1$) was found. An interaction between the two was also absent ($F(1,30) = 1.97, p > .17$). The accuracy analysis over all trials revealed no significant main effect of Time ($F<1$) or group ($F(1,30)= 2.04, p > .16$) and neither was the interaction effect of time with group ($F(1,30) = 1.12, p > .30$). In the accuracy analysis of the switch cost, the main effect of Time ($F<1$) and Group ($F(1,30) = 1.29, p = .723$) were not significant and also no significant Time*Group interaction was found ($F(1,30) = 1.91, p = .178$). In the accuracy analysis of the mix cost, the main effects of Time ($F(1,30) = 1.99, p = .169$) and Group ($F(1,30) = 3.97, p = .056$) were not significant and again no significant Time*Group interaction was found ($F<1$).

Verbal fluency task. In the L1 condition, the main effect of Time ($F(1,23) = 3.00, p = .097$), the main effect of group ($F(1,23) = 1.08, p > .30$) and the interaction between the two ($F<1$) were not significant. In the L2 condition, results revealed a significant main effect of Time ($F(1,23) = 4.50, p < .05$): the number of words produced was significantly higher in the post-test than in the pre-test. There was, however, no significant main effect of Group ($F(1,23) = 1.38, p > .25$) or Time*Group interaction ($F(1,23) = 3.82, p = .063$). In the mixed-language condition, analyses did not yield a main effect of Group ($F(1,23) = 1.30, p > .26$) or Time ($F<1$). Neither was there a significant interaction effect of Time and Group ($F(1,23) = 1.07, p > .31$).

In the analyses of the language switch cost (amount of produced words in the single language conditions - the amount of produced words in the mixed-language condition), no main effect of Group was found ($F<1$), but there was a main effect of Time ($F(1,23) = 6.79, p < .05$): switch cost was significantly higher at the post-test in

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[2] When behavioural RTs are analyzed with a blocked approach, as in the neuroimaging data, no effect of time or group was observed either.

comparison with the pre-test. However, this difference can be attributed to more fluent L2 production and stable mixed language production in the post-test and is therefore not really a reflection of less fluent switching at Time 2. There was no Time*Group interaction ($F(1,23) = 1.18$, $p > .67$).

Neural data

fMRI results

The whole brain fMRI analysis (Table 4) revealed a higher involvement of the left superior temporal gyrus in the Simon task (Figure 1) and a higher involvement of the right angular gyrus in the colour-shape switch task (Figure 2) after 9 months of SI training, compared to translators, despite the absence of differences between the two groups before their training. In the opposite direction, the translators only showed a higher involvement of the right cerebellum compared to SIs in the Colour-shape switch task after nine months of training (Figure 2). Note, however, that these brain regions were only significant at the uncorrected cluster level. In the verbal fluency task, no significant interactions were found.

Structural Connectivity results (NBS analysis)

Two set of regions (component/subnetworks) showed a significant increment of the structural connectivity for SIs as compared to translators at p < 0.01 FWE corrected (Figure 3). The first component (subnetwork I) interconnected frontal regions with basal ganglia, comprising a total of 5 regions (Figure 3a): left superior frontal gyrus (SFG); left/right medial superior frontal gyrus (SFGmed); left orbital superior frontal gyrus (SFGorb) and the right pallidum. The second component (subnetwork II) involved 8 nodes (Figure 3b): left supplementary motor area (SMA); right postcentral gyrus (PoCG); right SFG; right middle temporal pole (TPOmid); right amygdala (AMYG), vermis 3 of the cerebellum; left inferior parietal gyrus (IPG) and superior parietal gyrus (SPG).

Translators did not show any set of regions with an increment of the interconnectivity, relative to SIs. Schematic representations of the subnetworks are depicted in Fig. 3 using BrainNet version 1.5 (Xia et al., 2013,

http://www.nitrc.org/projects/bnv/). The anatomical name by which each node is labeled was taken directly from the Anatomical Automatic Labeling (AAL) atlas (Tzourio-Mazoyer et al., 2002).

DISCUSSION

We aimed to investigate whether SI may boost cognitive control, using a well-controlled longitudinal design in which SI experience was manipulated over time within the same participants. We included two highly similar groups of multilinguals with high levels of second (L2) and third (L3) language proficiency, but different language control needs. One group consisted of participants enrolled in a translator program, whereas the other group was following a simultaneous interpreting program (SI). As SI is often associated with extreme language control (Elmer et al., 2011; Woumans et al., 2015), we hypothesized that these students would show both behavioral and neural differences compared to translators after their nine-month training course. With regard to behavioral changes, we assumed that practicing SI would enhance domain-general cognitive control and verbal cognitive control. We also predicted that functional changes in activation of cognitive control related brain areas would occur, together with a modification of structural connectivity between brain regions that are involved in cognitive control of language.

Our expectations were, however, only confirmed at the functional and structural neural level, not at the behavioral level. We did not observe any cognitive behavioral advantages in SIs compared to translators. This finding replicates the majority of previous findings that failed to observe significant differences between SIs and other multilinguals on tasks relying on inhibition (Babcock & Vallesi, 2017; Dong & Xie, 1014; Morales, Padilla, Gómez-Ariza, & Bajo, 2015; Yudes, Macizo, & Bajo, 2011).

Analyses at the functional level revealed small but interesting differences after 9 months of training in SI or translation. Note however, that these differences did not survive the stringent threshold for multiple comparisons. Compared to the translators, the SIs showed an increase of activation in the right angular gyrus in the color-shape switch task, and an increase in activation in the left superior temporal gyrus in the Simon task. Increased activation in these areas in these tasks has been interpreted as a reflection of increased capacity of cognitive control functions (Rubia et al., 2006). Translators only showed an increase of activation in the right cerebellum in the color-shape switch task after nine months of training, relative to the SIs.

Interestingly, the left superior temporal gyrus, a region that is typically involved in a broad region of language processes, including the auditory perception of language switches (Abutalebi et al., 2007), appeared to show more activation in the non-verbal Simon task after nine months interpreting training than after nine months translating education. Furthermore, in previous literature, better interference suppression during incongruent trials of the Flanker task is also associated with higher activation in the superior temporal gyrus in bilinguals (Luk, Anderson, Craik, Grady, & Bialystok, 2010).

The functional increase of activation in the right angular gyrus during a task that relies on the inhibition of irrelevant information after 9 months of interpreting training supports the important role of the angular gyrus in the capacity to switch between languages. This was already highlighted in by Pötzl (1925), who revealed that lesions in the anterior angular gyrus lead to language-switching deficits. Additionally, the angular gyrus is not only reported to be connected to language control, but also to supramodal attentional control (J. J. Green, Doesburg, Ward, & McDonald, 2011) and supramodal semantic control (Noonan, Jefferies, Visser, & Ralph, 2013). Della Rosa et al. (2013) confirmed these findings at the structural level and did show that changes in gray matter values in the angular gyrus depend on the relationship between multilingual competence scores and attentional control scores. Therefore they concluded that the angular gyrus is a neural interactive location for multilingual talent (Della Rosa et al., 2013).

Most interestingly, at the structural level, we found a significant increase of connectivity for the SI's in two different subnetworks. This increment in FA values for the SI's are in line with our hypotheses, but opposite to the direction of connectivity effects in the previous study of Elmer et al. (2011a), who found lower FA values for SI's in comparison to their multilingual control group.

The first network consists of five interconnected nodes: the right pallidum, the left superior frontal lobe, the left superior orbital frontal lobe, and the right and left medial superior frontal lobe. The right pallidum, a substructure of the basal ganglia, seems to be a central node in this network, since all projections to the frontal regions seem to depart from this region. The second network consists of eight interconnected nodes: the right postcentral lobe, the Vermis 3, the left superior parietal lobe, the left inferior parietal lobe, the left SMA, the right amygdala, the right superior frontal lobe, and the right

middle temporal pole. In this network, the Vermis (a substructure of the cerebellum) and the SMA seem to be the central nodes between all connections.

The central role of the pallidum and the connection with frontal regions in the first anatomical subnetwork confirms the inhibitory control function attributed to this network in previous research. For instance, Aron et al. (2007) showed that the pallidum was involved in stop and go processes, whereas Atallah, Frank, and Reilly (2004) also highlighted the importance of the pallidum in the suppression of competing responses. Atallah et al. (2007) even proposed a cognitive model (the cortico-striato-thalamo-cortical loops model) in which the basal ganglia and frontal regions work together as one cooperative system to obtain cognitive control. In this system, the basal ganglia act as a modulator of the frontal regions, by facilitating the appropriate responses and suppressing the competing responses that are being considered by the frontal regions. Lehtonen et al. (2005) additionally showed that the pallidum is not only important for the suppression of competing responses in non-verbal cognitive control, but also for verbal control. They found that the pallidum was specifically involved during translation. These findings confirm the idea that the basal ganglia and its interplay with frontal regions are essential for domain-general cognitive control and language control. Furthermore, this overlap in brain regions confirms the cross-talk between language control and domain general executive cognitive control as proposed in the inhibitory control model of Green (1998). Therefore we can conclude that language control is a crucial mediator that may reshape the neural circuitry responsible for cognitive control.

This recruitment of highly similar brain regions during tasks that rely on language control and tasks that rely on domain general cognitive control is also supported by De Baene, Duyck, Brass, and Carreiras (2013). They argued that the recruitment of similar brain circuits during language control and cognitive control provide powerful evidence that the challenges of language control can shape the brain regions on which cognitive control relies. This is a plausible explanation for the reported bilingual advantage on tasks that rely on domain-general executive cognitive control (Bialystok, Klein, Craik, & Viswanathan, 2004; Bialystok, 2006; Bialystok, Craik, & Luk, 2008; Costa et al., 2008).

The involvement of the second subnetwork is a bit more unexpected, because in previous research the cerebellum was mostly found to subserve the coordination of

autonomic and somatic motor functions instead of language or cognitive control (Ackermann, Mathiak, & Riecker, 2007; De Smet, Paquier, Verhoeven, & Mariën, 2013; Fabbro, Moretti, & Bava, 2000; Mariën et al., 2014; Murdoch, 2010). However, most previous studies completely neglected this region and did not try to fit the cerebellum within the scan window. In contrast, Green and Abutalebi (2013) proposed a language control network, in which several areas of the second network (specifically, also the cerebellum, the SMA and the parietal lobes) also play a key role. In this model, the SMA initiates speech in language switching and the parietal lobes are connected to the maintenance of task representations.

Note, however that the structural and functional analysis revealed distinct findings. The cerebellum seems to be involved in both analyses, but unexpectedly in opposite directions, with an increased involvement of the cerebellum during the colour-shape switch task for the translators and an increased connectivity of the cerebellum for the SI's. Additionally, the increased involvement of the right angular gyrus during the color-shape switch task and the increased involvement of the left superior temporal gyrus during the Simon task was only apparent in the functional analysis, but not in the structural analysis. A possible explanation could be that translators and interpreters differ in the way they rely on the neural network. The connectivity between the cerebellum and other brain regions might for example become stronger for the interpreters. Therefore a shift could occur from relying solely on the cerebellum to relying more on the exchange between the cerebellum and other regions.

It is important to emphasize the conservative approach adopted here, to compare SI students with a group of closely matched translators from the same Bachelor program, rather than a monolingual or less L2-proficient control group. As a result, the obtained differences between these two highly similar groups need to be attributed to control processes that are specific to SI. In SI, a one-time presentation of an utterance in a source language (SL) is instantly rendered into an utterance of similar meaning in a target language (TL). According to Christoffels and de Groot (2005) and de Groot and Christoffels (2006), inhibitory control plays a crucial role during this rendition. The authors describe possible inhibition accounts of SI, assuming (functionally) distinct input and output lexicons that can be separately activated and inhibited. These accounts state

that both SL and TL input lexicons should be activated, to allow for input comprehension and output monitoring, while the SL output lexicon should be strongly inhibited. Other explanations for the observed differences between the SI and the translators are the development of a more efficient divided attention system or language switching system. This is because besides the proposed role of inhibitory control, an SI's attention is divided or switches rapidly between the different processes (Pöchhacker, 2004; Hiltunen, Pääkkönen, Gun-Viol, & Krause, 2016). Therefore, future studies are necessary to determine the specific processes that distinguish translating from SI.

The lack of behavioral differences between the two groups could similarly be explained by our conservative approach comparing two highly similar groups of SIs and translators, with the exact same prior education. Translating is not totally different from SI. Translators, too, have to render a source text into a target text, and when they are formulating this text in the target language (TL), they need to inhibit the source language (SL) at the output level, while keeping it activated at the input level. Essentially the process appears the same, but the amount of extreme language control is different between the two groups. SIs have to perform this process in real-time, i.e. immediately after or simultaneous with reception of the source text, making SI much more challenging (Babcock & Vallesi, 2017).

Additionally, it is possible that further experience could create behavioral differences that did not yet appear after only nine months of SI training, especially because the amount of SI practice was still limited during this Master course. Another possibility is that SIs recruit brain regions in a more efficient way, resulting in the observed functional activation differences, but that there are no behavioral differences between SIs and translators, because both already perform close to individual ceiling. Note that the lack of behavioral findings within our longitudinal design may also have been influenced by the demonstrated low test-retest reliability for the Simon effect, and somewhat higher test-retest reliabilities for the switch cost and mix cost (Paap & Sawi, 2016).

The lack of behavioral group differences in the inhibition task replicates the longitudinal findings of Dong and Liu (2016) and Babcock et al. (2017) who used a similar conservative approach comparing SIs with translators. However, in contrast to our results and those of Babcock et al. (2017), in the study of Dong and Liu (2016) the SIs

improved significantly more on switching than the translators. In future research, it may be interesting to also investigate tasks that tap into different types of inhibitory control (ex: ANT, flanker task, stroop task, go/no-go task) or switching-flexibility (ex: WCST) (Miyake & Friedman, 2012).

To conclude, given this longitudinal design with closely matched groups of SIs and translators, who received the same previous education, the observation of neural differences over the course of only nine months is really remarkable. Our results suggest that SIs undergo neural changes in specific control-related brain networks to handle the extreme language control that takes place during interpreting.

TABLES

Table 1. Language pairs that the simultaneous interpreters and translators received during the training program.

Participant	Language pairs
SI 1	German - Turkish
SI 2	German - Russian
SI 3	French - Spanish
SI 4	German - Italian
SI 5	English - Italian
SI 6	French - Italian
SI 7	French - Italian
SI 8	French - German
SI 9	German - Russian
SI 10	English - Russian
SI 11	French - German
SI 12	English - Italian
SI 13	English - Spanish
SI 14	English - Russian
SI 15	English - Spanish
SI 16	English - French
SI 17	French - German
SI 18	French - Spanish
TR 1	English - German
TR 2	English - Russian
TR 3	German - Spanish
TR 4	English - German
TR 5	English - German
TR 6	German - Spanish
TR 7	English - Spanish
TR 8	English - Spanish
TR 9	English - Russian
TR 10	French - Italian
TR 11	English - German
TR 12	French - German
TR 13	French - German
TR 14	English - German
TR 15	English - French
TR 16	English - German
TR 17	English - German
TR 18	English - French

SI = Simultaneous interpreter; TR = translator

Table 2. Means and standard deviations of the participant's demographic data. The self-ratings are on a 5-point likert scale and are summed across listening, speaking, reading and writing.

	SI	Translators	Test	P
N	18	18		
Male/female ratio	4/14	6/12	$Chi^2(1) = 0.55$	$p > .05$
Age	21.4 (0.6)	21.9 (1.4)	$F_{1,34} = 2.06$	$p > .05$
L2 AOA	9.8 (1.2)	9.5 (2.0)	$F_{1,34} = 0.23$	$p > .05$
Amount of languages	3.8 (0.7)	3.5 (0.5)	$F_{1,34} = 0.98$	$p > .05$
Self-Ratings L1 proficiency	19.75 (1)	20 (0)	$F_{1,34} = 1$	$p > .05$
Self-Ratings L2 proficiency	15.31 (1.54)	16.31 (1.62)	$F_{1,34} = 3.21$	$p > .05$
Self-Ratings L3 proficiency	13.88 (1.67)	14.62 (1.63)	$F_{1,34} = 1.66$	$p > .05$

Table 3. Mean RTs and accuracy rates for the Simon task and the color-shape switch task and mean amount of produced words for the verbal fluency task. Standard deviations of all measures are in parentheses.

	T1		*T2*	
	SI	Translators	SI	Translators
Simon task				
RT Simon effect	34 (32)	18 (44)	29 (29)	43 (29)
RT Congruent	510 (86)	529 (111)	492 (95)	439 (31)
RT Incongruent	544 (85)	547 (79)	522 (84)	482 (42)
Accuracy Simon effect	0.2 (0.8)	0 (1.2)	0.1 (0.4)	0.5 (0.8)
Color-shape switch task				
Mix cost	125 (93)	104 (85)	109 (89)	128 (64)
Switch cost	121 (68)	126 (74)	124 (79)	100 (48)
Accuracy all trials	96.3 (3.3)	97.4 (2.6)	95.1 (5.7)	97.5 (2.5)
Verbal fluency task				
L1 block	27.3 (9.4)	25.2 (7.9)	30.5 (6.7)	26.5 (7.6)
L2 block	21.5 (5.8)	17.2 (4.9)	21.7 (5.5)	21.3 (5.9)
Switch block	20.5 (3.6)	18.2 (4.2)	19.9 (3.4)	19.5 (3.9)

Table 4. Results of the fMRI whole brain analysis. Significant group x time interactions for the BOLD responses in the colour-shape switch task and the Simon task.

| Task	Coordinates	Area	*Z*	Cluster size	*p*
Colour-shape switch task					
Interpreters > Translators	48 -58 37	R Angular gyrus	3.51	162	.008**
Translators > Interpreters	24 -58 -23	R Cerebellum	3.82	168	.007**
Simon task					
Interpreters > Translators	-45 -25 4	L superior temporal gyrus	4.05	161	.004**

**p<.01

FIGURES

Figure 1.
Results of the whole brain searchlight analysis showing brain areas in which the interpreters showed more activation than the translators for the contrast incongruent relative to congruent trials in the Simon task. The color represents the *t*-values resulting from the group level analysis using a threshold of *p* < .005 at voxel level and an uncorrected cluster level for the whole brain at *p* < .05.
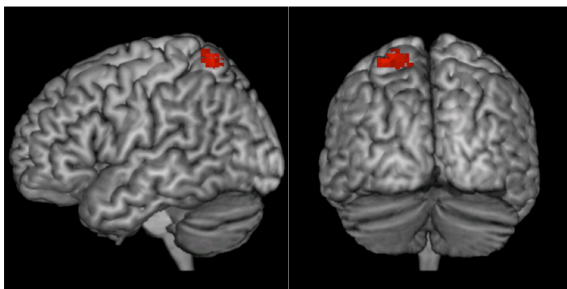
Figure 2.

Results of the whole brain searchlight analysis showing brain areas in which the interpreters showed more activation than the translators (red) and brain areas in which the translators showed more activation than the interpreters (blue) for the contrast task mix block, relative to task A and task B blocks in the color-shape switch task. The color represents the t-values resulting from the group level analysis using a threshold of $p < .005$ at voxel level and an uncorrected cluster level for the whole brain at $p < .05$.
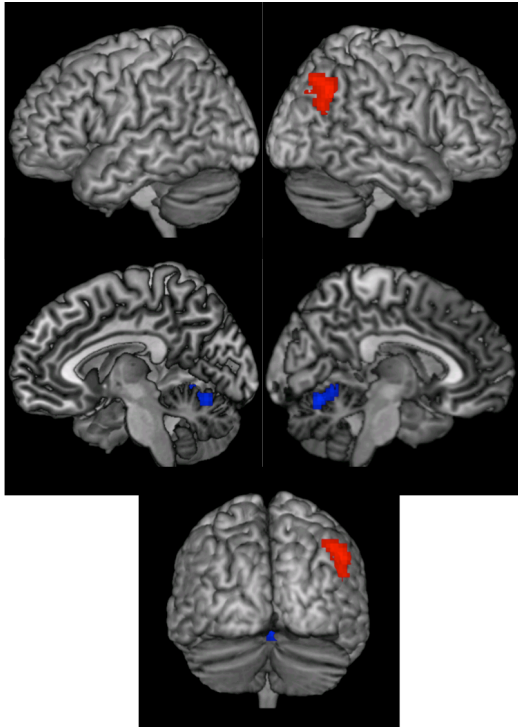
Figure 3.

Results of the network-based statistical analysis over the structural brain graph. Subnetworks showing increased structural connectivity in simultaneous interpreters as compared to translators (T-threshold=3, K= 10000 permutations, p < 0.01 FWE corrected). A) Subnetwork I: regions forming an individual component with 5 nodes/regions and 4 edges/connections. B) Subnetwork II: regions forming and individual component with 8 nodes/regions and 7 edges/connections. Abbreviations: L, left; R, right; SMA, supplementary motor area; SFGdor, superior frontal gyrus; SFGmed, medial superior frontral gyrus; SFGorb., orbital superior frontal gyrus, PoCG, postcentral gyrus; IPG, inferior parietal gyrus; SPG, superior parietal gyrus; TPOmid, middle temporal pole; AMYG, amygdala.
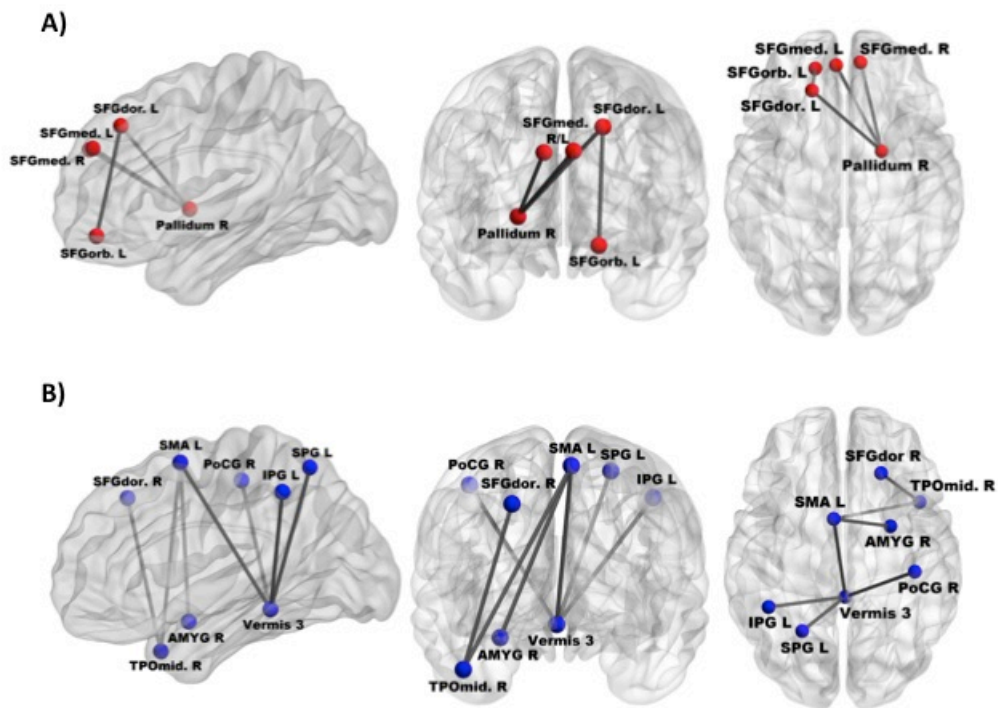
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